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AN ANALYSIS OF THE DIGITAL DATA COMMUNICATIONS LINK REQUIRED FOR THE AUTOMATIC DEPENDENT SURVEILLANCE SYSTEM CONCEPT AND THE AIRBORNE APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

by

GUSTAVO A. ANAYA

B.S., The Ohio State University, 1991

A thesis submitted to the

Faculty of the Graduate School of the

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has been approved for the

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by

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Harvey Gates

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Jon Sauer

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Peter MacDoran

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An Analysis of the Digital Data Communications Link Required for the Automatic Dependent Surveillance System Concept and the Airborne Applications of the Global Positioning System

Thesis directed by Dr. Harvey Gates

Significant changes will be occurring in the next ten years regarding air navigation and aircraft surveillance. The Global Positioning System, a worldwide satellite-based radionavigation system which provides positioning, navigation, and time information, has emerged as a reliable and incredibly precise means of air navigation which has seen widespread acceptance around the world. With GPS, aircraft can determine their position much more accurately than is possible with ground radar surveillance systems. The current Air Traffic Control system, however, is established in its use of radar surveillance and navigation routes are defined by ground navaids which limit efficiency.

The full benefits of GPS navigation cannot be realized without the Automatic Dependent Surveillance system concept. This is a new approach to Air Traffic Control in which every aircraft periodically broadcasts its GPS derived position so that ground controllers and other aircraft in the vicinity can receive and use this information. ADS has the potential to completely replace rotating surveillance radars with fixed omnidirectional antennas for receiving aircraft broadcasts.

The key to successfully implementing ADS depends on having a dependable digital data communications link. It is crucial to have an effective mechanism for transmitting aircraft position to air traffic controllers which utilizes equipment that is inexpensive, and yet is effective enough to serve the capacity needs of the system and reliable enough to not compromise safety. Finding the optimal solution to this problem is the biggest issue relating to air traffic control in the near term.

Satellite communications systems offer wide coverage areas but are prohibitively costly for many in the aviation world. Using a VHF data link using TDMA can achieve a notable capacity and is relatively inexpensive. In my opinion, however, the option of using Mode-S transponders, with new extended squitters, appears to be the best way to implement the ADS system concept. Mode-S has significantly more capacity than VHF and is comparable in cost.

I dedicate this thesis to my brother Alex and my sister Christina

both of whom I love very much.

ACKNOWLEDGMENTS

I would like to express my appreciation to the members of my thesis committee, Professors Peter MacDoran, Jon Sauer, and Harvey Gates. I am especially indebted to my thesis chairman, Dr. Harvey Gates, for all of his advice and research suggestions, and for allowing me access to research facilities and workspace at BDM Federal, Inc. I would also like to collectively thank those who took the time to answer my questions and to send me information.

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CHAPTER 1

INTRODUCTION

The Navstar Global Positioning System (GPS) is a worldwide, satellite-based radionavigation system which provides positioning, navigation, and time information. The satellites and their ground support equipment are funded by the United States government and controlled by the Department of Defense (DOD), but the navigation signals can be used by anyone who has a GPS receiver available. It was declared operational by the DOD in December 1993, and although the system was designed for military use, it has since seen widespread acceptance by civilians in the aviation community. This was formalized in February 1994, when the Federal Aviation Administration (FAA) announced that GPS-based instruments would now be certified as part of the U.S. National Airspace System.[1] The supplemental use of GPS has already been approved for en-route navigation and non-precision approach. Dependence on GPS navigation was cemented by the unilateral decision in June 1994 to cancel development of the microwave landing system (MLS) in favor of a GPS based solution.[2] Many avionics manufacturers have developed and produced affordable GPS receivers, providing further evidence

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[1] Palumbo, Dan, "Digital Avionics," *Aerospace America*, December, 1994, page 42.

[2] Warwick, Graham, "The Heart of the Matter," *Flight International*, October 5, 1994.

that GPS will definitely have a great impact on future modifications in the air traffic control (ATC) system.

The United States is not alone in the race to replace today's ground-based systems. The International Civil Aviation Organization (ICAO) established a special committee for the development of the Future Air Navigation System (FANS), a global plan intended for worldwide implementation of communication, navigation, surveillance, and air traffic management (CNS/ATM). The world aviation community has agreed that in the future, air transportation must be satellite-based. An integral part of FANS is the concept of automatic dependent surveillance (ADS), which makes use of satellite technologies.

ADS is a whole new approach to air traffic control. Using ADS, GPS equipped aircraft will continually transmit their positions and other information to ATC via digital data link. Instead of using ground-based radar and navigation aids, controllers will rely on the aircraft's position report obtained from the GPS satellites.[3] This will significantly reduce the overall cost of aircraft surveillance. An important choice, which still has yet to be made, is what digital data link to use to transmit this ADS information. The ICAO plan states that the data link may be via satellite communications, the secondary surveillance radar's Mode-S, or very high frequency (VHF) radio.[4]

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[3] Nordwall, Bruce D., "Digital Data Links Key to ATC Modernization," *Aviation Week and Space Technology*, January 10, 1994, page 53.

[4] FANS Phase II Report - Fourth Meeting, International Civil Aviation Organization, October, 1993, page 7A-20.

A dependable digital communications standard is needed. I believe that this is the biggest issue relating to air traffic control in the next few years. The proper design of this communications channel is the key to the successful application of the ADS system concept. It is crucial to have an effective mechanism for transmitting aircraft position to air traffic controllers which utilizes equipment that is inexpensive, and yet is effective enough to serve the capacity needs of the system and reliable enough to not compromise safety.

Affordability is a considerable factor in finding a solution which can be applied on a universal basis. Complete implementation of an ADS-based system is impossible unless all aircraft are equipped with a digital data communications link. General aviation, the less affluent members of the flying world, cannot be left out. It has to be recognized that we risk air safety in the future if the needs of all aircraft are not represented.

The capacity of the data link chosen is also a substantial consideration. The method used must be able to work in airspace which varies from minimal to extreme traffic densities. The amount of air traffic will only increase in the future, demanding that the method of data communications have sufficient capacity, therefore providing assured safety.

The purpose of this thesis is to achieve an optimal solution to the problem of determining the digital data communications standard which will be used in implementing ADS. An overview of related systems is included, as well as a discussion of the potential data links which have been proposed. I will make a

comparative analysis of the strengths and weaknesses of satellite communications, Mode-S, and VHF data links. I will then describe what the practical capabilities of the future systems will be. While satellite communications will be used mostly on oceanic routes, either the Mode-S or VHF data link will be used over continental regions where line-of-sight transmissions are possible. I believe that it is important to have a *single* standard chosen for this data communications link, just as there is a single standard language (English) for aeronautical voice communications.

I will use a research methodology for this thesis which is analytical, involving an examination and systematic interpretation of a wide array of sources. Publications from the International Civil Aviation Organization, the Radio Technical Commission for Aeronautics, the U.S. Department of Transportation, and U.S. Department of Defense, in addition to information obtained from relevant periodical publications and Congressional hearings will be examined and analyzed. Conversations with members of the above organizations as well as with others, including product manufacturers who are currently conducting related research, will be interpreted also. Some background information was discovered and gathered by examining relevant books.

In this thesis, which I have organized into chapters, I will discuss the nature of the ATC system under a satellite-based navigation environment. I will begin with a short description of the current methods of exercising air traffic control and attempt to bring out those problems which might be solved by the application of Global Navigation Satellite Systems (GNSS), in particular GPS and its

implementation using ADS. Then a description is given of the concepts of GPS and the ADS system concept. I will then review the new techniques and systems most likely to satisfy the requirements of this air navigation system, and the way in which they will fit into the overall picture. More specifically, I will investigate the techniques proposed for establishing a digital data communications link between aircraft and ATC. I will describe the extent to which these techniques have been or are being evaluated. From this substantiative analysis, the goal is to develop logical conclusions and present them to the reader in an intelligible and concise manner.

CHAPTER 2

BACKGROUND / AIR TRAFFIC CONTROL

The principle purpose of an air traffic control service is to prevent collisions between aircraft, or between aircraft and obstacles, and to expedite and maintain an orderly flow of traffic.[1] This is achieved through both pre-flight planning and in-flight guidance. Whenever a flight plan is filed and a pilot flies his aircraft into the sky, he becomes a part of the air traffic control system. If flying under instrument flight rules (IFR), the aircraft will be on a controller's radar screen somewhere.

Each controller is responsible for maintaining safe aircraft separation, keeping the traffic moving expeditiously, and monitoring aircraft to make sure they are flying the maneuvers or flight plans prescribed. They accomplish this by using radio, radar surveillance equipment, and computer systems. The radio, used for direct speech between controllers and pilots, is the most fundamental component. This is the means by which pilots tell controllers where they are and what they want to do and controllers give instructions and clearances. Pilots can also receive by radio the latest weather information over their route or give pilot reports of turbulence or icing they are experiencing.

Radar surveillance equipment, which provides aircraft position information, is also heavily relied upon in the present ATC system. Controllers using radar

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[1] Farmer, J.C. and Whitney, M.F., "Data Handling for Air Traffic Control," *The Proceedings of the Institution of Electrical Engineers*, 1960, page 2.

surveillance equipment work in three basic facilities: airport towers, terminal radar approach control (Tracon) installations, and en route control centers. Collectively this is know as the radar beacon system. Airport surveillance radar (ASR), which is used at terminal facilities, has a range of about 60 miles. There are about 20 en route control centers in the U.S. which use surveillance radar with a range of several hundred miles and these cover all the airspace above 18,000 feet.

The computer systems process information from the radar surveillance equipment, transponders on aircraft, and flight plans filed by pilots before flight. Each aircraft's location, speed, and other information is then displayed for the controller. A controller could probably keep track of five or six planes by watching just the raw radar returns, but in order to monitor the traffic loads common during peak periods it is necessary to have the help of these computer systems. Controllers in airport towers and Tracon installations rely on the automated radar tracking system (ARTS) computers, first installed in the middle 1970's.[2]

The safety and efficiency of ATC depends on the controller's ability to analyze a complex situation and make a quick decision regarding the future movement of an aircraft. This requires that he have accurate and current information, which is dependent on the available air-ground communications and surveillance capabilities. Most problems occur during the busiest traffic periods, especially when there are bad weather conditions. If a single controller has about 25 or 30 pilots all on a frequency, which is not uncommon, it could be half a

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[2] Fischetti, Mark A., "Our Burdened Skies," *IEEE Spectrum,* November 1986, page 38.

minute before any particular pilot can get a word in. This can affect both safety and efficiency. The following is a pilot describing an experience of his in high traffic airspace:

> "I come into Los Angeles," he said, "and I am given a clearance I cannot comply with. No way are we going to make that altitude; we're going to bust it, and we're going to bust it big. The frequency was full--I don't know how many airplanes that controller had--but there was no way to break in and tell him." By the time the frequency opened, he said, his plane was a thousand feet off its assigned altitude. All the while, he said, "I was sweating like hell [worrying about colliding with another plane.]"[3]

This exemplifies the seriousness of congested radios.

In the airspace over oceans and even some continental areas around the world where there are flights operating outside radar and VHF coverage, ATC keeps separation of aircraft by procedural methods. Flights are monitored by using the aircraft's current flight plan and position reports (at infrequent intervals) from the pilot. These are transmitted via high frequency (HF) voice communications, which are not limited by line of sight but have severe interference and fading problems.[4] Because of the lack of precise positioning information resulting from current inaccuracies, controllers are required to maintain a bubble of airspace fifty miles in diameter between all aircraft operating over the oceans.[5] This leads to inefficiency. Using procedural methods to keep aircraft separated is not very

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[3] Perry, Tekla S., "The Real World," *IEEE Spectrum,* November 1986, page 46.

[4] Automatic Dependent Surveillance Circular, International Civil Aviation Organization, 1990, page 1.

[5] "Future Uses of Satellite Technology in Aviation," Hearing before the Committee on Public Works and Transportation, 103rd Congress, first session, July 28, 1993, page VIII.

flexible, consequently the routes traveled are not necessarily the most direct or the most economical.

Even in airspace which has reliable VHF communications and radar surveillance systems such as here in the U.S., flights are not always as direct as they could be and inefficiencies result. This is because airways through which aircraft fly are defined by ground-based navaids such as a VHF omnidirectional range/distance measuring equipment (VOR/DME), tactical air navigation (TACAN), collocation of both (VORTAC), or non-directional beacon (NDB). Flying from one navaid to another until reaching a destination adds time and distance to the trip, and therefore increases operating costs. According to the U.S. Air Transport Association, the present ATC system costs airlines between $3.5 billion and $5 billion a year.[6]

After the en route portion of a flight comes the approach and landing phase. The most common and accurate landing system in use today is the instrument landing system (ILS). This provides both localizer and glideslope information and is used for precision approaches, allowing landings with reduced ceilings and visibilities. Most major airports are equipped with at least one ILS but most smaller airports are not. If an aircraft's destination airport does not have instrument approach capability and the weather goes bad there, it is necessary to divert to another airport. This is definitely less than optimal for all people involved.

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[6] Warwick, Graham, "Navigating the Future," *Flight International*, August 31, 1994.

The current methods of exercising ATC, using ground-based systems, has proven over the years to be relatively safe. However, with the number of flights today and the demand for even more flights in the future, I feel that the air traffic system as it exists has reached its capacity for providing assured safety. Many of the problems that are inherent in the current ATC system are simply related to efficiency. I have summarized the problems in safety and efficiency as the following: congested radios in busy terminal areas, airspace without sufficient surveillance, indirect routing because of ground-based navaids and excessive separations, and lack of all-weather landing capabilities at most airports.

Flying Nirvana

In a satellite-based navigation environment, using ADS, aircraft would use GPS receivers and then transmit there position automatically to the air traffic facilities via a digital data link. This will produce many substantial benefits to ATC, including greater accuracy in determining position and velocity of aircraft and worldwide surveillance capability covering even areas far out of range of radar. The digital data link will also be used to automatically exchange routine messages between aircraft and ATC, therefore alleviating the overloading of radio frequencies. Potentially, as all relevant information is displayed for both pilot and controller, there would no longer be a need for talking except possibly in an emergency. The improved precision will cause modifications in how air traffic is managed, allowing aircraft to be able to fly closer together than before and along

more direct and fuel efficient routes than possible now. Flights will become less dependent on the fixed airways defined by ground-based navaids and will use user-preferred trajectories, sometimes referred to as a "free flight" concept. This will reduce operating costs and increase capacity. Using GPS, there will be improved access to airports as all-weather landing capability becomes available at many places not now equipped with an ILS. Most importantly, the use of this satellite technology will enhance the safety of flight by permitting highly accurate conflict prediction by the ground-based computer systems and possibly by airborne collision-avoidance systems.

Some additional benefits could be considered as secondary, however they are still significant. Search and rescue operations would be assisted substantially by having emergency locator transmitters (ELTs), which are already in aircraft, also transmit the last GPS position calculated. Also, more accurate winds aloft data could be automatically transmitted from aircraft, allowing better selection of routes and altitudes and calculation of required fuel loads for flights being dispatched.[7] Besides these mentioned, even more benefits are sure to be discovered and used to the advantage of all in the flying world.

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[7] Ferguson, Robert R., "GPS," Continental Airlines Position Paper, June 14, 1993, page 3.

CHAPTER 3

CONCEPTS OF GPS

The Navstar Global Positioning System satellites and their ground support equipment are funded by the United States government and controlled by the Department of Defense. Research and development for GPS was initiated to solve the problems of its predecessor, the Transit system, also called the Navy Navigational Satellite System (NNSS), which had periods of time without coverage and had relatively poor accuracy. Transit has a constellation of ten satellites, but operation of the system will be terminated by the DOD in December 1996.[1]

To provide continuous, worldwide positioning information it was necessary to ensure that at least four satellites were in view at all times. The solution was to have a satellite constellation of 24 satellites in 12 hour circular orbits, 10,898 nautical miles above the earth in six orbital planes, each of which is tipped 55 degrees with respect to the equator. The GPS satellites are configured so that users can determine their position, expressed in latitude, longitude, and altitude. This is done using triangulation of the distances measured from the user to the satellites.

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[1] U.S. Federal Radionavigation Plan, U.S. Department of Transportation and U.S. Department of Defense, 1992, page 3-31.

In this chapter I will explain this concept of satellite ranging and triangulation, including how we measure the distances to satellites and how we know where the satellites are in space. I will describe some of the sources of errors in the position calculations and how we can correct for them. I will then analyze the signal structure and discuss the codes transmitted by the GPS satellites. I will finish by analyzing the methods that are being used or are proposed to be used for ensuring that the signals are reliable and have integrity. But first, I will give a brief description of the components of the GPS system, which is most commonly divided into three major segments: the space segment, the control segment, and the user segment.

System Description

The 24 GPS satellites in orbit around the earth are considered the space segment. Of these, 21 are operational and 3 are active spares which can be used if a malfunction occurs with a satellite. There are also spares on the ground which can be launched if necessary. Individual satellites can remain operational for about ten years.[2] The satellites in the constellation are Block II satellites, which are bigger, more powerful, and have a longer lifespan than the previous Block I satellites. The important difference is in the transmitted signal, which can be restricted on the Block II satellites, which possess the selective availability / anti-spoof capability

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[2] Hofmann-Wellenhof, Lichtenegger, and Collins, Global Positioning System: Theory and Practice, Springer-Verlag Wien, New York, New York, 1993, page 15.

(SA/AS) explained later. Block IIR satellites will be *replacement* satellites and will have more accurate clocks and better communications.

The satellites are provided power by solar panels which charge their batteries so they can perform several basic functions. They receive and store information transmitted by the operators of the system. They do a certain amount of processing on board by means of its own microprocessor. Atomic clocks are on board so they can maintain very accurate time and they have thrusters so they can be maneuvered by the system operators. They also must transmit information to the users by means of various signals.[3]

The atomic clocks are an important part of the GPS satellite. The Block II satellites have two cesium and two rubidium clocks which must be and are incredibly accurate. These clocks are so stable that they would lose or gain only about one second every 160,000 years.[4] Even so, clock correction factors are still transmitted from the ground. The time maintained aboard the satellites is synchronized relative to master clocks located at the U.S. Naval Observatory in Washington, D.C. and the National Institute for Standards and Technology in Boulder, Colorado.[5] When the Block IIR satellites are put into orbit, they are

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[3] Wells, David, Guide to GPS Positioning, Canadian GPS Associates, Fredericton, New Brunswick, Canada, 1987, page 4.1.

[4] Logsdon, Tom, The Navstar Global Positioning System, Van Nostrand Reinhold, New York, New York, 1992, page 15.

[5] MacDoran, Peter F., and Matthews, Michael B., "GPS, The Magnificent New Tool That Cuts Two Ways," keynote address to *GPS World* Conference, 19 May, 1993, Denver, Colorado, page 2.

expected to have on-board hydrogen masers which will be at least one order of magnitude more precise than the atomic clocks in the Block II satellites.[6]

The control segment consists of five monitor stations, three control stations, and one master control station which manages the satellite constellation. The

Figure 3.1 GPS Control Stations
Source: Wells, David, Guide to GPS Positioning, Canadian GPS Associates, Fredericton, New Brunswick, Canada, 1987, page 4.9.

master control station is in Colorado Springs, Colorado at Falcon AFB. The five monitor stations are evenly spaced around the world at Hawaii, Colorado Springs, Ascension Island, Diego Garcia, and Kwajalein (see figure 3.1). The latter three of these locations are control stations as well as monitor stations. The functions of the control segment are to track the GPS satellites, to keep them in their correct orbits,

[6] Hofmann-Wellenhof, page 15.

to make sure the satellite clocks are synchronized, and to transmit data messages to the satellites (including their ephemeris coordinates).

Each monitor station has an atomic clock and its precise location is well known. They continuously measure the distance to all GPS satellites in view and transmit this information to the master control station which can then determine the ephemerides of the satellites and any clock errors. This information is then uploaded to the satellites from the control stations.

The user segment is essentially all of the receivers which can process signals from the GPS satellites. Most receivers are multi-channel and can take information from four or more satellites. Each channel will lock on a separate satellite and track it continuously. Then it can calculate accurate time, position, and velocity and display it to the user. The accuracy of the receiver depends on a number of errors which can occur and factors such as the type of code it uses, C/A-code or P-code, which will be described later.

Satellite Ranging

The way that GPS receivers are able to determine their three-dimensional location is by satellite ranging. Once the receiver knows its distance to the satellites, triangulation is used to calculate position. The receiver measures the time it takes for the signal to arrive from a satellite and can then calculate its distance, since the speed of this electromagnetic wave is known (the speed of

light).[7] If we know the distance to only one satellite, then we know that we are somewhere on the sphere of that radius around that satellite (see figure 3.2). If we know the distance to two satellites, we are somewhere on the sphere around each and our possible position is now narrowed down to the circle of points where these two spheres intersect. Knowing our distance to a third satellite will similarly limit our possible position to two points on that circle. One of these answers will not be logical and can be disregarded, therefore our location is at the other point. This is the concept of triangulation. For this to work as described, however, we are assuming two things: we have accurately measured the distance to each satellite

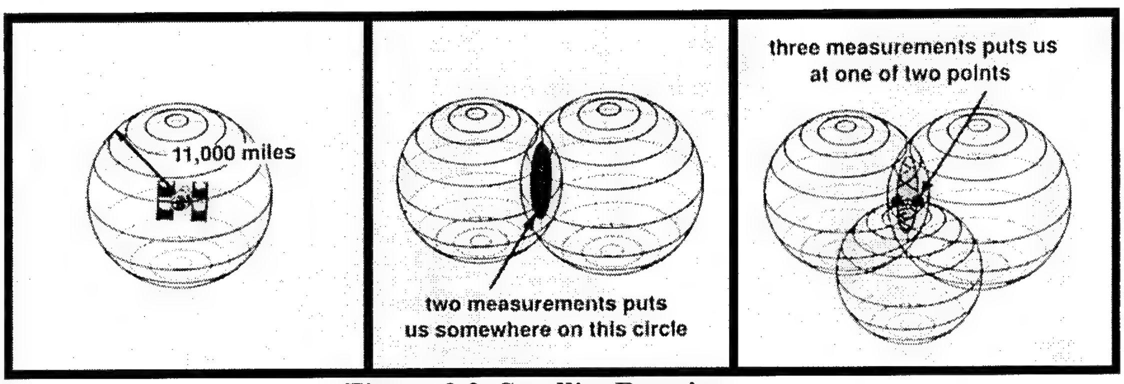

Figure 3.2 Satellite Ranging

Source: Hurn, Jeff, GPS: A Guide to the Next Utility, Trimble Navigation, Sunnyvale, California, 1989, page 15.

and we know where each satellite is when it transmitted its signal. Below I will explain why we need to measure the distance to a fourth satellite in order to accurately know our location.

Because the distance measurements are calculated using the time of signal travel, it will only be correct if the clock on the satellite and the clock on the

[7] Wells, page 4.11.

receiver are perfectly synchronized. This is almost never the case, since it would be too expensive for receivers to contain the precise atomic clocks which are on the satellites. Consequently, the ranges measured to the satellites are not the true distances and are referred to as pseudoranges. If we know the pseudoranges to four satellites, we can mathematically eliminate this error caused by the receiver clock not being synchronized. Now our timing measurements will yield the accurate results we want. That is as long as all of the satellite clocks are synchronized, which explains why all the expense for such precision. One interesting note is that the satellite clocks have purposely offset ticking rates to compensate for the relativistic effects which occur in accordance with Einstein's general and special theories of relativity.[8]

The other necessity for triangulation is knowing where the satellite is when it transmits its signal. Generally each satellite's position is very predictable by using Kepler's three laws of orbital mechanics and by taking into account perturbing forces acting on satellites such as the effect of the earth's equatorial bulge, the attraction of the moon and sun, solar radiation pressure, and atmospheric drag.[9] There are deviations, however, which are observed by the monitor stations, uploaded from the control stations, and then transmitted by the satellites in their signals to the receivers. Now the receiver knows the exact ephemeris coordinates of the satellites.

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[8] Logsdon, page 23.

[9] Wells, page 5.0.

Some receivers make use of a technique called receiver autonomous integrity monitoring (RAIM). Using RAIM is a way to check the integrity of satellite data by comparing information from five or more satellites. As stated before, only four are needed to solve a position calculation. The fifth satellite will not increase the accuracy of the receiver, but it will give the receiver the capability of determining whether any satellite is broadcasting erroneous information.

Sources of Error

I have already mentioned some sources of error, associated with receiver and satellite clocks and orbital ephemerides, and how we make the necessary corrections. In this section I will describe some other sources of error which occur.

The earth's atmosphere can be a source of problems, causing propagation errors. The ionosphere and troposphere create delays in the GPS signal that can translate into errors in position.[10] The ionosphere bends and slows the signal slightly resulting in a time delay inversely proportional to the square of the transmission frequency; therefore, transmitting two frequencies (L_1 and L_2) and using programmed mathematical corrections, P-code receivers can extract nearly all the delay.[11] Mathematical modeling that can lessen some of the delay is used in C/A-code receivers, which can only accept the L_1 frequency. The delay caused by

[10] Hurn, Jeff, GPS: A Guide to the Next Utility, Trimble Navigation, Sunnyvale, California, 1989, page 47.

[11] Logsdon, page 24.

the troposphere varies according to how much atmosphere the signal must pass through. Receivers can use a mathematical correction to account for this which is a negative exponential function of altitude and a cosecant function of the elevation angle above the local horizon.[12]

One other source of errors which I will discuss is actually a geometric consequence of using satellite ranging and triangulation. It is the effect of the

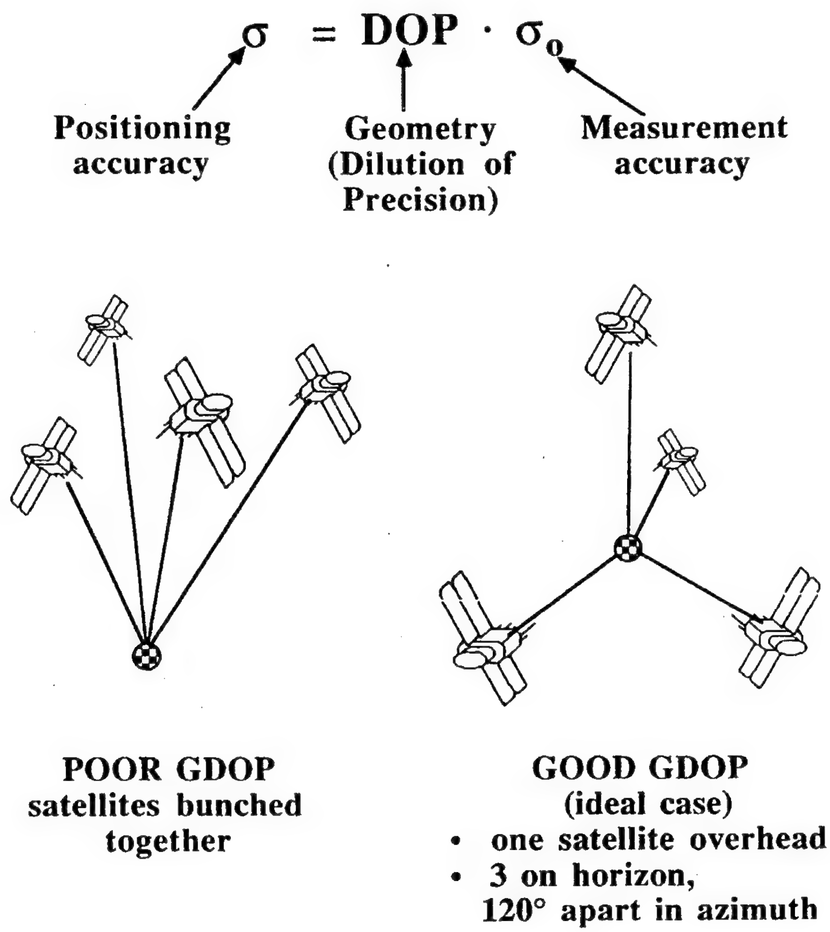

Figure 3.3 GPS Geometry and Accuracy
Source: Wells, David, Guide to GPS Positioning, Canadian GPS Associates, Fredericton, New Brunswick, Canada, 1987, page 4.22.

[12] Logsdon, page 25.

satellite configuration, which constantly changes with time as the satellites proceed on their orbits. There is a loss of positioning accuracy because of geometric calculations which involve satellites that are not in the best place with respect to the user. There is a term called the geometrical dilution of precision (GDOP) which is a numerical measure of the instantaneous contribution of the configuration geometry.[13] The geometry is good when the satellites being tracked are spread out in the sky and it is bad when they are bunched together or in a straight line in the sky (see figure 3.3). Receivers attempt to pick the four most favorable satellites to track in order to minimize the GDOP. The global time average for the Navstar's GDOP is about 2.3 for a 24-satellite GPS constellation.[14] This is significant because this factor is *multiplied* by the measurement accuracy (calculated from satellite ranging) to get the three-dimensional positioning accuracy (see figure 3.3).

One of the biggest sources of error is an intentional degradation that is controlled by the DOD. These methods have been termed selective availability / anti-spoof (SA/AS). Selective availability limits the capabilities of unauthorized users to make accurate measurements of the pseudoranges to satellites. This is accomplished by either "dithering" the clock information of the satellite or by distorting the ephemeris coordinates which are transmitted. Anti-spoofing protects the military against the possibility of enemies sending false signals and causing users to misinterpret their position. Anti-spoof denies access of the P-code

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[13] Wells, page 4.22.

[14] Logsdon, page 29.

(described in the next section) to civilians by converting it to a classified Y-code which needs a secret conversion algorithm to use. Civilians are left with using the less precise C/A-code.

Signal Structure

Each satellite in the constellation is continuously transmitting electromagnetic waves toward the earth. The signals have a *spread spectrum*, which means that the information content is transmitted over a much wider bandwidth than would be necessary ordinarily. Spread spectrum is a modulation technique in which an input signal is taken, mixed with FM noise, and "spread"

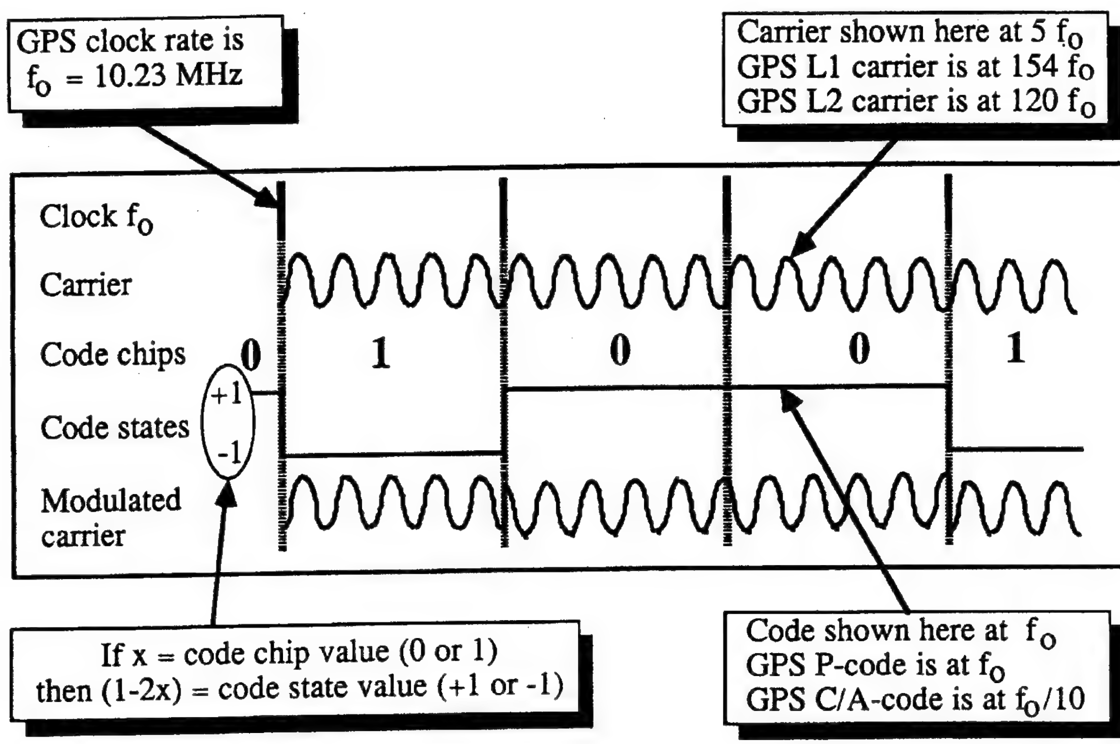

Figure 3.4 Code Modulation Technique
Source: Wells, David, Guide to GPS Positioning, Canadian GPS Associates, Fredericton, New Brunswick, Canada, 1987, page 6.3.

over a broad frequency range.[15] This makes the signal less prone to interference, whether intentional or not. The signal spreading method used by GPS is called direct sequence spreading and uses a pseudo-random noise (PRN) code and binary biphase modulations.[16] This means that the signals are phase modulated using 180 degree phase shifts to indicate a change in binary code (see figure 3.4). Over this spread spectrum, the satellites transmit their position, their time, and this pseudo-random code.

The noise codes are called pseudo-random because they have many of the qualities, including a small autocorrelation, of random noise. The difference is that the autocorrelation function of random noise is zero while that of the PRN code is not. The same PRN codes are generated at the same time in both the satellites and the receivers by a carefully specified algorithm, hence by using a mathematical correlation of the two, the receivers can shift the timing until the codes match. This time shift corresponds to the travel time of the signal (see figure 3.5) and can then be used to calculate a range measurement.

Two pseudo-random binary sequences are used to transmit the satellite clock readings. These are the coarse/acquisition code (C/A-code) and the precision code (P-code) mentioned earlier. These are unique for each satellite so the receivers know which satellite is which. The C/A-code, transmitted on a single frequency and sometimes referred to as standard positioning service (SPS), is the

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[15] Newton, Harry, Newton's Telecom Dictionary, Telecom Library Inc., New York, New York, page 837.

[16] Wells, page 6.2.

code available for civilian users. The P-code, transmitted on dual frequencies and sometimes referred to as precise positioning service (PPS), is only available, through the use of encryption techniques, to the U.S. military and others who are authorized. While the C/A-code will repeat each millisecond, the P-code will repeat only about every 266 days. The code length is divided into week-long segments and each unique segment is assigned to a satellite defining its PRN number.[17]

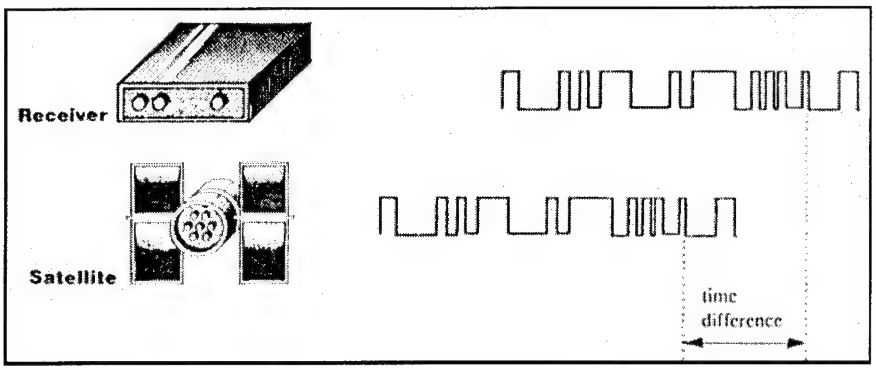

Figure 3.5 Pseudo-random Code

Source: Hurn, Jeff, GPS: A Guide to the Next Utility, Trimble Navigation, Sunnyvale, California, 1989, page 20.

Because each satellite is generating its own unique C/A-code and P-code, it is possible for all the satellites to use the same two carrier frequencies. Code Division Multiple Access (CDMA) is used to distinguish the satellites from one another.[18] The fundamental frequency of the broadcast signal is a result of the highly accurate clocks on board the satellite, whose oscillations produce the fundamental L-band frequency of 10.23 MHz. The L_1 (1575.42 MHz) and L_2

[17] Hofmann-Wellenhof, page 73.

[18] Logsdon, page 20.

(1227.6 MHz) carrier frequencies used by GPS are multiples of the fundamental frequency. They have wavelengths of about 20cm (L_1) and 25cm (L_2), and the data transmitted on these carriers occupies about 20 MHz of the spectrum on each channel.[19] The P-code is modulated onto both the L_1 and L_2 carrier and the C/A-code is modulated onto the L_1 carrier in phase quadrature (90 degree offset) with the P-code.[20] Besides these PRN codes, the carriers also have a data message modulated onto them.

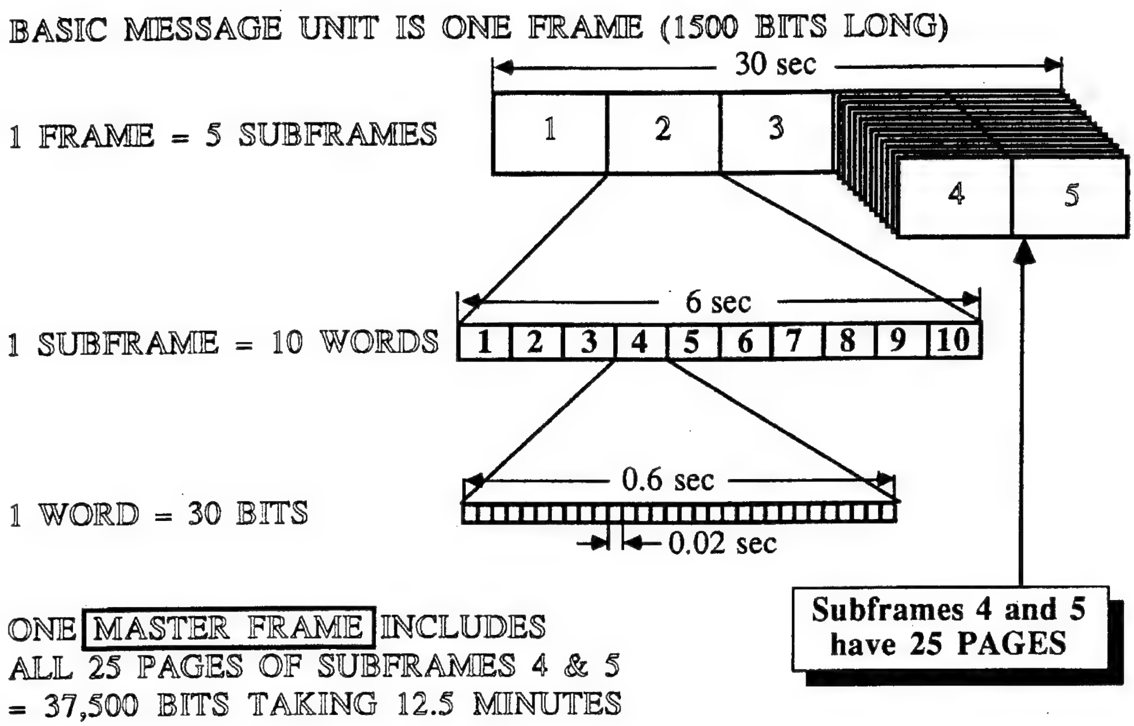

Figure 3.6 GPS Message Format

Source: Wells, David, Guide to GPS Positioning, Canadian GPS Associates, Fredericton, New Brunswick, Canada, 1987, page 6.5.

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19 Newton, page 423.

20 Hofmann-Wellenhof, page 71.

This data message has a transmission rate of 50 bps and is formatted into frames of 1500 bits (see figure 3.6). Each frame, taking 30 seconds to transmit, is divided into 5 subframes. The first three frames contain information which does not usually change from frame to frame, such as the system time, satellite clock corrections, and ephemeris coordinates. The last two frames contain constantly changing information such as ionospheric modeling coefficients, health status of the satellites, and other flags and almanac data.[21] A master frame is 25 complete frames and takes 12.5 minutes to transmit.

Differential GPS

Even with the high accuracy of GPS, some applications require even more precise position information. For these applications, what is called differential GPS (DGPS) may be used. The U.S. Coast Guard was the first pioneer into DGPS,[22] however NASA, the FAA, commercial entities, and others have also done successful experiments. DGPS augments GPS by using ground reference stations, called base stations, in conjunction with the GPS satellites. This allows the capability to yield measurements good to a couple meters in moving situations and even better in stationary situations.[23]

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[21] Hofmann-Wellenhof, page 74, and Wells, page 6.6.

[22] Hurn, Jeff, Differential GPS Explained, Trimble Navigation, Sunnyvale, California, 1993, page 33.

[23] Hurn, page 11.

DGPS essentially is more accurate because it eliminates many of the sources of error which I described earlier. It does this by exchanging position information between two receivers, one of which is a base station whose position is geodetically surveyed and well known and the other of which is the operational DGPS receiver. The base station tracks all the satellites in view, downloads ephemeris data from them, calculates its GPS position, and compares it to its known location. The difference is a result of any errors. Now it computes corrections and broadcasts these errors to the other receiver to improve its navigation solution.[24] Because the satellite ephemeris and clock bias errors will be the same for the two receivers, these sources of error will be eliminated. DGPS even corrects for the intentional degradation of the signals that occur when selective availability is activated[25]and that is the largest source of error. For ionospheric and tropospheric delays, the correction factor transmitted from the base station can eliminate most of the errors in the second receiver. There need not be a base station for every DGPS receiver; a base station serves as a static reference point so that all DGPS receivers in the vicinity can obtain error corrections.

To get an idea of the drastic difference that differential corrections can make in the positional accuracy of an aircraft, we need only to look at the results of tests that have been done. From figure 3.7, which compares the accuracy of GPS with DGPS, we can see that differential navigation can reduce errors in position to less

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[24] U.S. Federal Radionavigation Plan, page A-41.

[25] Hurn, page 22.

than 10 feet. The actual error depends on the distance between the two receivers, the speed that the error correction data can be exchanged, and the sophistication of the computer processing techniques.[26]

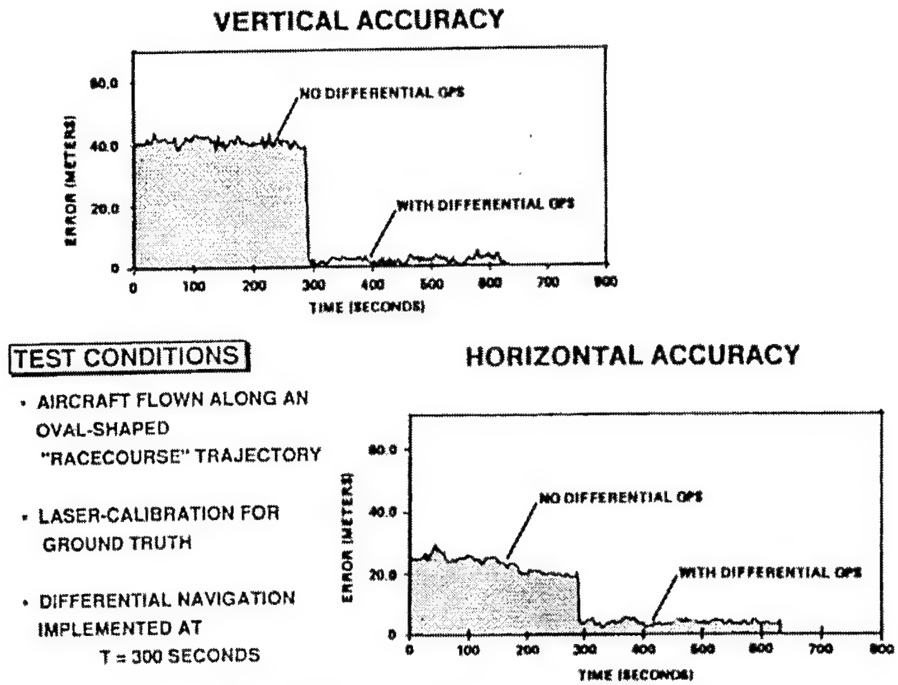

Figure 3.7 Differential Navigation Test Results

Source: Logsdon, Tom, The Navstar Global Positioning System, Van Nostrand Reinhold, New York, New York, 1992, page 77.

DGPS can be divided into two categories, local area differential GPS (LADGPS) and wide area differential GPS (WADGPS). The LADGPS systems operate by broadcasting corrections directly to the DGPS receivers as I have described above, while the WADGPS systems use satellite links to broadcast the corrections and therefore cover a much *wider area.* LADGPS will tend to have greater accuracy improvements (potentially to centimeters) than will WADGPS because of the shorter distance between base station and receiver. LADGPS will be

[26] Logsdon, page 76.

most likely located at airports and used for precision approaches, including under Category-2 and -3 conditions (requiring the most precision).

WADGPS will provide GPS integrity broadcast and accuracy improvements for whole continents. In North America, this is called the Wide Area Augmentation System (WAAS). It will consist of 24 DGPS ground stations which will be networked to a master station, where satellite integrity and (if the Pentagon allows) differential corrections will be calculated. This data will be transmitted via two geo-synchronous satellites (probably Inmarsat-3 satellites[27]), providing coverage of the entire U.S., including Hawaii, Alaska, and Puerto Rico. The integrity data will make the use of GPS for navigation extremely reliable. One of the main objectives of WAAS is to enhance GPS accuracy enough to allow it to be used for precision approaches under near Category-1 conditions at many airport runways not now equipped with ILS.[28] This can occur if differential corrections are broadcast. The signals which the aircraft will receive will be similar to a GPS signal with unique codes,[29] using the same L_1 frequency band.

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[27] "Using Inmarsat Transponders for Global Satellite Navigation," *Satellite Communications*, October, 1994, page 68.

[28] Klass, Philip J., "FAA Delays Awarding DGPS Network Contract," *Aviation Week and Space Technology*, January 30, 1995, page 35.

[29] U.S. Federal Radionavigation Plan, page A-48.

CHAPTER 4

ADS SYSTEM CONCEPT

There will soon be a fundamentally different approach to air traffic control, made possible by Global Navigation Satellite Systems such as GPS and its Russian equivalent, the Global Orbiting Navigation Satellite System (GLONASS). As stated earlier, ICAO has developed a global plan for implementation of communication, navigation, surveillance, and air traffic management (CNS/ATM) called the Future Air Navigation System (FANS). Its objective is to provide guidelines for the transition from the current ground-based air navigation system to the future satellite-based system. FANS is based on the two-way digital transmission of data between aircraft and air traffic services on the ground. It is essentially built on the concepts of GNSS, the aeronautical telecommunications network (ATN), and automatic dependent surveillance (ADS). In this chapter, I will give a brief overview of the ATN and then explain the ADS system concept and how it works.

Here in the United States, the FAA has stated that their mission is to provide a safe, efficient, and responsive aviation system, and they specifically list out their goals for the future National Airspace System (NAS) as the following:[1]

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[1] GPS Implementation Plan for Air Navigation and Landing, Federal Aviation Administration, U.S. Department of Transportation, August, 1994, page 3.

- Maintaining or improving the safety of flight operations
- Accommodating user-preferred flight profiles to save both time and fuel
- Increasing airport and airspace capacity to meet future air traffic demands
- Satisfying the needs of the full spectrum of aviation users

By using GPS and ICAO's concept of an ADS-based system, all of these goals can be accomplished, provided that an appropriate data communications link is used which can "satisfy the needs of the full spectrum of aviation users." I will wait until the next chapter to actually analyze the proposed methods to be used for this data communications link, however ICAO states the probable possibilities as: satellite communications, Mode-S, or VHF data link (see figure 4.1).

Aeronautical Telecommunications Network

The concept of ADS could be considered a component, albeit a very important one, of the aeronautical telecommunications network which has been defined by ICAO in their FANS plan. ATN is the architectural basis for global aeronautical data communications which will bring together into one integrated network the communications between aircraft, air traffic services, airline operations networks, and more. The ATN's most familiar parallel is the internet, in the sense that messages or information packets will be carried on an infrastructure of air-to-surface links and ground-to-ground links in a shared network of many nodes, or addresses, and these ATN nodes can be located anywhere: at an ATC installation, on an aircraft, at the gate, or in a hanger.[2] Once on the ground, the information will

[2] Sweetman, Bill, "Airlines Get Connected to ATN," *Interavia Aerospace World*, March, 1994, page 45.

not only be available to ATC but can be directed via the ATN to any other appropriate facility, such as an airline or corporation wishing to keep tabs on their fleet. Having these two-way, addressed messages going through the ATN sounds great. However, for it to work, it will require both airborne and ground routers, referred to as communications management units, which will connect the end users through the ATN and ensure reliable message delivery.

ICAO plans to adopt the open systems interconnection (OSI) model of data communications and implement it into the ATN. OSI is an internationally accepted framework for developing protocol standards, being developed by the International Organization for Standardization. It consists of a seven-layer model. ICAO sees the main benefits of using the OSI model as:[3]

- inter-operability between different computer systems and peripherals
- exchange of information on a global basis
- freedom to choose innovative products

Utilizing commercial "off the shelf" technology which conforms with the OSI model is also much more economically feasible than having a specially developed, dedicated communications system. This is important if the ATN is to truly become a *worldwide* aeronautical data communications network.

The development of the ATN will take time and effort, but the process is being led by the FAA. The FAA has entered a cooperative agreement with a consortium of U.S. airlines, which will develop ATN components and associated

[3] FANS Phase II Report - Fourth Meeting, page 4-7.

test products with FAA funding and technical resources.[4] Of course, implementation will have to take place first in small subnetworks which will become operational at different times around the world and will serve only certain specific needs. Only as these subnetworks all become interconnected will there actually be the ATN hoped for which is available and usable both domestically and internationally.

Part of the ATN concept is the communications management unit, mentioned earlier, which would obtain necessary information from the aircraft avionics and route it to the ground. Reliable communications with aircraft are essential, and there are many applications that could take advantage of addressed messages, a feature of the ATN. However, there are some times, such as when information is intended for a large amount of users at the same time, that it is just more efficient to broadcast the messages. It also would seem better to broadcast messages that are repetitive and updated frequently.

This is where the ADS system concept comes in. How long it will take to get to the seamless "internet" of the ATN is another thesis, but the concept of ADS is very achievable in the near term and is a dire necessity if we are to reap all the benefits that we can from GPS. Additionally, ADS messages can be either addressed or broadcast; the operating environment and application dictating which is chosen.

[4] Nordwall, page 53.

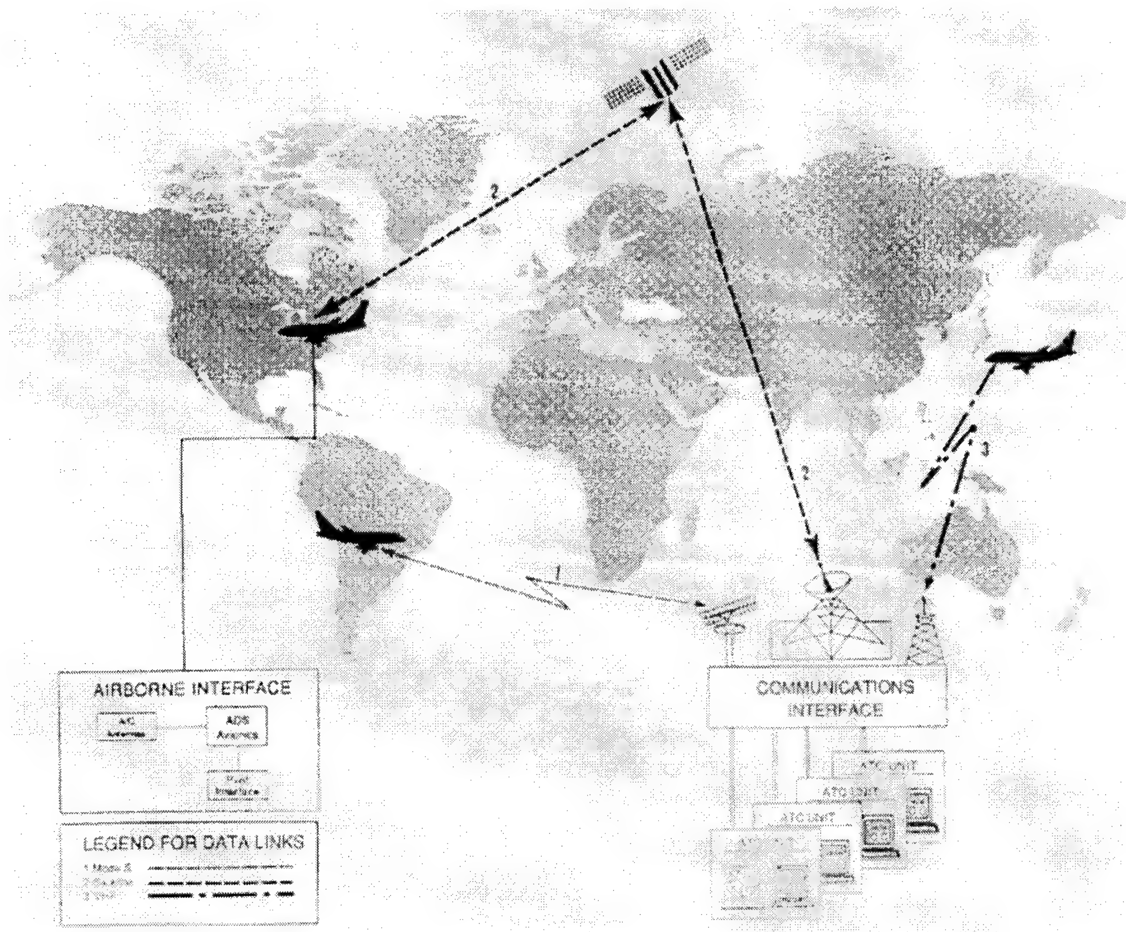

Figure 4.1 ADS System Concept

Source: Automatic Dependent Surveillance Circular, International Civil Aviation Organization, 1990, page 4.

Basic Concept

The concept of ADS (see figure 4.1) is based on the availability of air-ground digital data link communications, as defined by ICAO:

> Automatic dependent surveillance is a function for use by air traffic services in which aircraft automatically transmit, via a data link, data derived from on-board navigation systems. As a minimum, the data include aircraft identification and three-dimensional position. Additional data may be provided as appropriate.[5]

[5] Automatic Dependent Surveillance Circular, International Civil Aviation Organization, 1990, page 3.

The additional data mentioned should include the ability for pilots and controllers to send messages to each other. Therefore, the two functional elements of ADS are aircraft surveillance and the communication of messages. Consequently, the ADS function must be near real time to be useful and practical.

The frequency of the passage of information could be determined to be any of four different ways: by contract between the aircraft and ATC, on-demand immediate response, time ordered polling, or random access. ICAO expects that the "contract mode" will be the best for ATC purposes.[6] This means that the aircraft would give ADS reports based upon a prearranged agreement of certain intervals of time or based upon certain events, such as reaching a way-point or passing an altitude, or even a combination of both methods. Of course, ATC will always have the ability to demand immediate response by interrogating the aircraft and the pilot will always have the ability to send an ADS report. Most ADS reports, however, will be transmitted automatically without the need for human involvement, just as the name implies.

Establishing this contract for communications between aircraft and ATC is possible by the use of addressed messages, which complies with the ATN concept. Broadcasting ADS messages, however, allows aircraft to transmit their position information to anyone in the local area who is capable of receiving it. Although the broadcasting of this data does not strictly conform to the ATN concept of airborne and ground routers, it is the better means of transmission in many situations.

[6] ADS Circular, page 7.

Basic ADS Report

Data Elements	To be transmitted: Every report	On request	Resolution
Latitude / Longitude	X		0.0125′
Altitude	X		2.4 m (8 ft)
Time	X		0.125 s
Figure of merit	X		
Field activation / ADS capability		X	
Flight identification		X	

Extended ADS Report

Data Elements	To be transmitted: Every report	On request	Resolution
Next way-point		X	0.0125′
Estimated altitude at next way-point		X	2.4 m (8 ft)
Next + 1 way-point		X	0.0125′
Estimated altitude at (next + 1) way-point		X	2.4 m (8 ft)
Track / heading		X	0.1°
IAS / Mach		X	0.5 kt/0.001
Vertical rate		X	0.08 m/s

Associated ADS report

Data Elements	To be transmitted: Every report	On request	Resolution
Wind speed		X	2 km/h (1 kt)
Wind direction		X	0.7°
Temperature		X	0.25°C

Figure 4.2 ADS Messages

Source: Automatic Dependent Surveillance Circular, International Civil Aviation Organization, 1990, page 10.

I stated that the functional elements of ADS are surveillance, which includes positioning information, and the communication of messages, which could include any related information. The basic report contains aircraft identification, latitude, longitude, altitude, time, figure of merit, and field activation/reporting capability flags (see figure 4.2). The aircraft identification is called the technical address, and is made up of a unique 24 bit combination.[7] The figure of merit reveals how accurate the positioning information is and the reporting capability flags tell what other information is included in the ADS report. This additional data can include things such as way-points, altitude changes, headings, velocities, and winds.

Implications

Using an ADS-based ATC system will have many advantages over methods in use today. Perhaps the most obvious is a the benefit of providing worldwide surveillance coverage. Non-radar environments such as over the oceans will have surveillance services accurate to 100 meters or less, this is very substantial when opposed to the accuracy of today (using procedural methods) which is measured in terms of miles. Oceanic ADS would undercut the need for the $384 million ARSR-4 long-range radar program which is in development.[8] There are also many places in the world besides the oceans where there are not ground-based surveillance

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[7] ADS Circular, page 11.

[8] Learmount, David, et al., "Controlling the World," *Flight International*, February 10-16, 1993, page 26.

capabilities; implementation of ADS avoids the high cost of building ground-based infrastructures in these areas.

Having this increased surveillance capability has several implications. It permits the early detection by air traffic controllers of aircraft which deviate off the course prescribed in their flight plan. President Reagan's decision to allow GPS signals to be used by civilians was actually in response to the Korean airliner which was shot down over the Soviet Union after it flew off course. Increased surveillance capability also implies that aircraft will be allowed to fly closer together and along more optimum routes (flying user-preferred trajectories), which improves efficiency and reduces delays. Reducing separation standards just over the Atlantic and Pacific oceans alone will save the airline industry $200 million annually in fuel expense.[9] Another benefit of this increased surveillance capability is enhanced search and rescue, a natural consequence of knowing more accurately the last known position of an aircraft.

In addition to the increased surveillance over oceans and remote areas will be the improved communications ADS will provide in comparison to having only HF voice communications. It will be more expeditious to amend a clearance, get updated weather information, or get help in an emergency situation.

ADS will have many implications over continental areas such as here in the United States and in Europe as well. Due to its implementation of GPS positioning information, there will be greater accuracy in determining the position and velocity

[9] "The Global Positioning System: What Can't It Do?," page 30.

of aircraft. This will lead to better conflict prediction which implies a greater degree of safety. Not having to rely on ground-based navigation aids will enable ATC to eventually allow aircraft to fly user-preferred trajectories (the "free flight" concept). This will allow for increased capacity and reduced delays. Delays caused by congestion and current ATC inefficiencies result in losses in excess of $3 billion each year in Europe alone and about $10 billion annually worldwide.[10]

Current enroute and terminal navigation systems consist of thousands of individual beacons and transmitters which are quite antiquated technologically.[11] Elimination of much of this equipment used today could save millions of dollars every year in maintenance costs. For example, it is estimated that each of the approximately 1,300 NDB equipped facilities spend a minimum of $50,000 each year in maintenance ($65 million annually).[12] That is only one of the many different types of equipment used in the current ground-based navigation environment which would not be necessary, another example being VOR/DME. Radar used as secondary surveillance may not even be necessary at some point. The annual maintenance cost for the current enroute radar system in the U.S. is $50 million per year.[13] The use of ADS will also help alleviate the overloading of radio

[10] LaFond, Charles D., "ICAO Sees Communication, Navigation, and Surveillance Functions Should Be Satellite-Based in the Future," *Air Transport World*, December, 1991, page 96.

[11] "Future Uses of Satellite Technology in Aviation," page IX.

[12] "The Global Positioning System: What Can't It Do?," page 31.

[13] "Future Uses of Satellite Technology in Aviation," page 26.

frequencies by providing the data link by which routine messages can be exchanged between aircraft and controllers.

Implementing ADS will allow for increased capacity in the world's airspace, while maintaining or improving the level of safety that exists presently. It will accommodate user-preferred flight profiles which save time and fuel. It provides the potential for the savings of millions of dollars. If all aircraft can be made ADS compatible, then the needs of the full spectrum of aviation users will be satisfied. In order to achieve this ultimate end, it must be affordable for all aviation users to equip their aircraft with a digital data communications link which is effective and reliable enough to meet the capacity needs of the system.

CHAPTER 5

DIGITAL DATA COMMUNICATIONS LINKS

Equipping every aircraft with a digital data communications link is compulsory in the transition to an ADS based system. This is a very massive task to undertake. It is necessary to have a mechanism for transmitting aircraft position to air traffic controllers which is effective enough to serve the capacity needs of the system, reliable enough to not compromise safety, and inexpensive enough to implement on universal basis. The new systems have to work for all types of aircraft, with different degrees of sophistication, and in all types of airspace, with different traffic densities. The potential data links which have been proposed include satellite communications, Mode-S transponders, and VHF data links. In this chapter I will make a comparative analysis of the strengths and weaknesses of each.

I will commence by describing the state of satellite voice and data communications, which will by necessity be the best alternative to the HF voice-only communications in use today over oceans and polar regions. Over most continental regions, especially in terminal areas which are more congested, the best alternative to today's radar surveillance systems seems to be one of two line-of-sight digital data communication link techniques. Some institutions favor a new VHF data radio system, while others would like to see the function built into the

Mode-S ATC transponder.[1] Most of this chapter will be devoted to making comparisons between these two techniques, in terms of their capacity, their demonstrated test results, and their cost of implementation.

SATELLITE COMMUNICATIONS

For much of the world, satellite voice and data communications capability will be a must. As I previously stated, there are areas where line-of-sight digital communications are not possible, thus requiring the use of satellite technology. It is also anticipated that in many of these areas, such as the Pacific and North Atlantic, there will be significant growth in aircraft traffic, thus requiring reliable and timely aircraft communications and position reporting. HF voice communications, although having the capability of over-the-horizon transmission, are greatly limited due to interference and fading problems. These HF voice communications which are in use today will be phased out in favor of satellite communications systems. This will make the implementation of ADS possible in this type of airspace, where the benefits are extremely substantial.

Already, the satellites for these systems and their supporting ground elements are well under development, as are the avionics which will be utilized in the aircraft. A leading provider of aeronautical mobile satellite systems is Inmarsat. Others providing satellites include Mobile Satellites in Canada, American Mobile Satellite Consortium, Multifunctional Transport Satellite in Japan, and Australian

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[1] Sweetman, page 45.

Satellite.[2] The airlines have been big buyers of satcom equipment, foreseeing significant financial savings in a satellite-based navigation environment and financial gains from the availability of passenger telephone services. The major suppliers of satcom equipment are Honeywell/Racal, which has sold more than 500 systems to 30 airline customers, and Rockwell Collins, which has sold more than 400 systems to 27 airlines.[3]

The Inmarsat aeronautical mobile satellite system consists of three geosyncronous satellites which provide almost complete global coverage, as well as the supporting ground earth stations. In addition to these three operational satellites are spares which are available if necessary. They use frequencies which are allocated for aeronautical use in the L-band and the VHF band. Inmarsat can support both data and voice. The system design uses a time division multiplexing / time division multiple access (TDM/TDMA) packet-transmission technique for data and signaling, while digital voice circuits use single channel per carrier / frequency division multiple access (SCPC/FDMA) transmission so it can take advantage of speech characteristics to minimize satellite resource demands.[4]

The Japanese Ministry of Transport also has been developing an aeronautical mobile satellite system which is designed to provide services in the

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[2] LaFond, page 98.

[3] Warwick, Graham, "The Heart of the Matter," *Flight International*, October 5, 1994.

[4] Wood, P., "Inmarsat's Aeronautical Satellite Communications System," Proceedings of the 4th International Conference on Satellite Systems for Mobile Communications and Navigation, London, England, October 17-19, 1988, page 79.

Asian and Pacific region. It is called the Multifunctional Transport Satellite (MTSAT). One of the major purposes of the MTSAT is to provide additional capacity to support ADS in that part of the world so that a reduction in ATC separation minima can be achieved.[5] This will result in an increase in the air traffic capacity in the North Pacific between the U.S. and Japan.

Operational trials using satellite communications for ADS are being done in the Pacific involving the USA, Japan, Australia, and other nations. United Airlines was the first airline which used a satellite data link to send position reports automatically on flights over the Pacific, using HF voice communications only as a backup.[6] The ADS messages were sent via an Inmarsat satellite to the Australian Civil Aviation Authority (CAA) where the aircraft was displayed and tracked on a screen. The trials were extended to include New Zealand, Fiji, Singapore, Russia, and Tahiti. The results of these trials were successful. More trials are continuing at the present time using Quantas Airlines Boeing 747-400 aircraft in the South Pacific.[7] The major goals being reduced aircraft separations and dynamic and flexible routing of aircraft. Besides Boeing, Airbus and McDonnell Douglas are involving their respective long-haul aircraft. In addition to United and Quantas, Air New Zealand and Cathay Pacific are also involved. It is hoped by all that full ADS capability will be available by April 1996.

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[5] FANS Phase II Report - Fourth Meeting, page 4-4.

[6] Learmount, page 32.

[7] Norris, Guy, "Watching the Clock," *Flight International*, November 16, 1994.

In the North Atlantic, the United Kingdom CAA is performing trials which apply satellite communications systems. The purpose of these trials, scheduled to be completed this year, is to confirm the operational capabilities of ADS and to validate the emerging ICAO Standards and Recommended Practices (SARPs) for aeronautical mobile satellite service and ADS in an ATN compliant environment.[8] This means the equipment has to comply with the OSI seven layer architecture. The aircraft used is a British Airways 747-400, the avionics used are manufactured by Honeywell/Racal, and the satellites used are Inmarsat. In conjunction with the United Kingdom CAA, the European Organization for the Safety of Air Navigation is keeping accuracy measurements in these trials to investigate the use of GPS to reduce the separation of aircraft.[9] Although detailed analysis of the data is still being done, it appears that the satellite voice and data communications link is performing very reliably.

Honeywell/Racal is assured that they can provide high quality and reliable voice and data communications anywhere in the world with their aeronautical satellite communications systems. These systems will support ADS by regular transmission of aircraft position, intent, and route information to ATC centers via a direct digital data link which, because of its "toll quality" communication, suffers none of the atmospheric afflictions of HF voice.[10] In addition to the benefits which

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[8] FANS Phase II Report - Fourth Meeting, page 4K-4.

[9] FANS Phase II Report - Fourth Meeting, page 4K-1.

[10] Honeywell Air Transport Systems Division, "Aeronautical Satellite Communications - Total Systems Solutions," Honeywell Inc., Phoenix, Arizona, 1993, page 3.

I have already mentioned that ADS can provide, they cite quick emergency response and the ability to fix operational problems in real-time as advantages of satellite communications. Also notable are the services which become available to passengers, which include facsimile, computer modem, and regular telephone calls while airborne.

In using satellite communications for ADS application, aircraft are directly connected with the controlling ATC oceanic facility. The messages are addressed and therefore a "contract" can be established as described in the previous chapter. ADS messages will be sent according to pre-determined time intervals or at specific way-points. Once the data link is established, it can be used for other applications such as weather services and en route clearances.

The biggest advantage of satellite communications remains that it has such a wide coverage area. On the other hand, its biggest drawback is that it is expensive. The typical cost to equip an aircraft with satellite communications systems is in the area of $400,000.[11] A MCS-6000 satellite communications unit from Honeywell/Racal costs $278,000,[12] the necessary antennas another $100,000, and then installation charges on top of all this. If it were not for this factor of its high cost, the problem of choosing a data communications link for implementing ADS would be solved. Satellite communications could serve the needs of everyone on a worldwide basis. Because of the high cost, however, the use of satellite

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[11] Conversation with Pete Conner of C3Sat International, San Antonio, Texas.

[12] Conversation with Rod Gunther of Honeywell Air Transport Systems Division, Phoenix, Arizona.

communications will mostly be in the oceanic and remote regions of the world where their use will remain necessary to implement ADS. Fortunately, these regions are only the domain of the airlines, the military, and large corporate aircraft. So while it is prohibitively costly for the pilot of a general aviation aircraft to equip it with satellite communications equipment, it is just as unrealistic that he would ever find himself on an oceanic route.

VHF DATA LINK

ADS, as I stated, does not require the use of satellite communications. Over most continental regions, the ADS messages can be transmitted via a line-of-sight digital data communication link. In this section I will investigate whether a VHF data link could be a better option than using Mode-S for this implementation of ADS. VHF frequencies have always been used for voice communications, being the cornerstone of air traffic control. The VHF channels which are designated for aeronautical use are in the 118 MHz to 136.975 MHz frequency range, allocated by the Atlantic City ITU (International Telecommunications Union) Radio Conference in 1947.[13] Some people feel that the transformation to an ADS-based environment could be obtained much more quickly by using VHF communications channels rather than Mode-S for a digital data link.[14] It may even be cheaper to implement.

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[13] RTCA Special Committee-172, Document 225 "VHF Air-Ground Communications System Improvements Alternatives Study and Selection of Proposals for Future Action," RTCA, Inc., Washington, D.C., November 17, 1994, page 9.

[14] Nordwall, page 54.

The cost of a time synchronized VHF data link could be only about $1500 to $3000 per aircraft.[15] The result, however, could be a sacrifice of the capabilities which would be desirable for a long term solution.

As I mentioned, VHF is used mostly just for analog voice. For this application, it is a very cost-effective and reliable communications medium. VHF radio communications are done in simplex push-to-talk fashion, which means that the same frequency is used to transmit and receive, but only one of these functions can be done at a time. The modulation technique used is double-sideband amplitude modulation (DSB-AM) without carrier suppression. Within the 19 MHz of spectrum allocated for aeronautical use, the channels are spaced 25 kHz apart. Although this yields a total of 760 different channels, it has been determined that there is a shortage of assignable aeronautical frequencies in some places. In North America and Europe, the demand for VHF communications has reached a level which is approaching saturation of the existing radio spectrum.[16] This is an important consideration when we are discussing the future use of this spectrum for aeronautical data link purposes. In an ADS environment with GPS space-based navigation, however, the ground-based radio navaids such as VORs would not be necessary and therefore the VHF frequencies used for this purpose in the 108 MHz to 117.975 MHz range could be available.

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[15] Newborg, Olov, "Datalink for GPS Relay," *Flight International*, March 3, 1993, page 1.

[16] RTCA Special Committee-172, Document 225, page 6.

The VHF band is already used today as a data link for air-ground and ground-air communications through the use of Aircraft Communications Addressing and Reporting Systems (ACARS). This is used for communications between airlines and their aircraft, and not used for ATC purposes. However, a VHF digital data link used for the purpose of ADS and controlling air traffic could use many of the same principles.

Aircraft Communications Addressing and Reporting Systems

ACARS is a data link system which operates in the VHF aeronautical band and allows communication of character-oriented data between aircraft and ground systems. ACARS is used today for airline operational control. It reduces the need for voice communications by allowing pilots to send arrival and departure times, fuel status, flight delay information, as well as other data to their airline command center. It provides the capability to receive data from the ground as well, such as weather information. Although I stated that ACARS is not used by ATC, there is at least one application which does make use of it at some airports; aircraft can receive their pre-departure clearance over ACARS and therefore reduce congestion on the voice radio frequencies.

An ACARS system is made up of the airborne avionics and a ground station network. The equipment which is needed in the aircraft is a communications unit, a control display unit, and a management unit. The communications unit which ACARS normally employs is a VHF transceiver and a VHF antenna, although

satellite communications equipment could also be used. The VHF frequency assigned for ACARS use is 131.550 MHz.[17] The pilot interfaces with the control display unit, through which he can enter information or see displayed information.

The ground station network consists of a service provider and the airlines' host computers. A service provider sets up a network of ground stations through which messages are routed to the airline's host computer system. Aeronautical Radio, Inc. (ARINC), Air Canada, and Avicom Japan are such service providers. SITA (Society of International Aeronautical Telecommunications) is an international data communications network which provides these services for most of the rest of the world. ARINC, with their electronics switching systems network of more than 275 VHF ground radio stations, provides continuous coverage above 20,000 feet over all the U.S. and parts of Canada and Mexico.[18] The transmissions received at these ground radio stations are demodulated and stored in a local memory buffer before a central processor gathers and routes the messages to an airline host computer system. Once the information gets to the airline's host computer system, it is available for all the users within the organization.

The actual ACARS messages have a maximum block length of 220 characters of text. Each character is coded in 7 bits as specified by ICAO and another bit is added to each character for parity. Since these messages are sent via

[17] Rockwell Collins Air Transport Division, "What Is ACARS?," Rockwell International, Cedar Rapids, Iowa, February 1, 1985, page 3.

[18] Nickum, James D., "Aeronautical Data Link: An Overview of the System, Its Operation, and Its Benefits," Rockwell Collins Air Transport Division, Cedar Rapids, Iowa, October, 1994, page 4.

VHF radio, ACARS operates in a simplex fashion just like VHF voice communications. When a message is ready to be sent from the aircraft, the airborne ACARS management unit listens to determine if the VHF channel is free of other communications traffic. If there is traffic then the system will wait to transmit the message. If two aircraft transmit a message at the same time then they will be garbled and each aircraft will have to retransmit their message. The ground radio station checks the message when it is received by performing a 'block check sequence' error check and if it is free of errors it will be routed to its destination by the central processor. The ground radio station then will send an acknowledgment signal (ACK) to the aircraft to let it know that the message was successfully received. If the airborne ACARS management unit does not receive this ACK then it will retransmit the message. The ACARS system will alert the pilot if a message is transmitted six times without receiving an ACK.[19]

I mentioned that the ACARS messages are made up of 220 characters of 8 bits. This digital data is encoded in the following way (see figure 5.1) before it is transmitted:

> Data 1's and 0's are encoded by differentially encoding 1200-Hz and 2400-Hz tones. Data 1's are represented by the negative half-cycle of the 1200-Hz tone and data 0's are represented by the positive half-cycle of the 1200-Hz tone. To provide a continuous waveform during transmission, the 2400-Hz tone is transmitted to indicate that there is no bit change.[20]

[19] Rockwell Collins Air Transport Division, page 8.

[20] Rockwell Collins Air Transport Division, page 24.

At the ground radio station, a demodulator decodes this analog VHF signal and returns it to a digital signal. The full advantage of digital modulation is not achieved, however, because of the need to reduce the modulation to the audio baseband for interfacing with existing DSB-AM transmitters and receivers.[21]

BIT ORDER	1	2	3	4	5	6	7	8	9	10	11
MESSAGE	0	1	0	0	1	1	1	0	0	1	0
WAVEFORM											

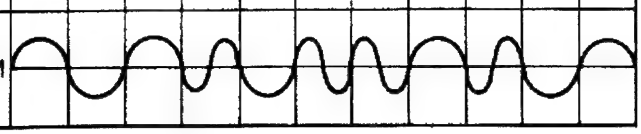

Figure 5.1 ACARS Encoded Waveform

Source: Rockwell Collins Air Transport Division, "What Is ACARS?," Rockwell International, Cedar Rapids, Iowa, February 1, 1985, page 25.

The ground-air transmissions work the same way as the air-ground transmissions, except that if errors are detected by the ACARS management unit by performing a block check sequence then it will send a negative acknowledgment (NAK) back to the ground radio station. Also, the airborne management unit will only respond to messages which contain that aircraft's specific address.

Current ACARS avionics work at a channel data rate of 2400 bps.[22] Experience has shown that a typical ACARS communication message takes less than a second to transmit and automated responses to a request for information can usually be returned within 10 seconds or less.[23] This is fast enough to serve the

[21] RTCA Special Committee-172, Document 224 "Signal-In-Space Minimum Aviation System Performance Standards (MASPS) for Advanced VHF Digital Data Communications Including Compatibility With Digital Voice Techniques," RTCA, Inc., Washington, D.C., September 12, 1994, page 13.

[22] RTCA Special Committee-172, Document 224, page 13.

[23] Nickum, page 2.

needs of ACARS present day uses, but it shows that it is not designed for real-time application. Also, the cost of an ACARS system is roughly $90,000[24] which is not practical if all aircraft, including the large population of general aviation aircraft, are to be equipped.

New System Characteristics

If there is to be a VHF data link used for ADS implementation, then there must be another option besides ACARS because of the high cost and other shortfalls inherent in the that system. The fact that ACARS is not designed for real-time is one of the deficiencies which was cited in reports by the Radio Technical Commission for Aeronautics (RTCA), which acts as a Federal Advisory Committee and whose membership represents a cross section of the aviation world, including both civil and military airspace users and equipment suppliers.[25] They also state that because it is a character-based system, it is not as efficient or flexible as a bit-oriented communications technique; it also is not directly compatible with the OSI model and the quality of service of ACARS cannot be easily improved. The new VHF digital data link used for ADS should be bit-oriented and based on OSI architecture.

RTCA has conducted studies to determine how this new VHF digital data link should work. They considered many options, keeping in mind that the current

[24] Newborg, page 1.

[25] Klass, Philip J., "RTCA to Evaluate Data Link Systems," *Aviation Week and Space Technology*, February 1, 1993, page 53.

voice capabilities must be maintained. The examination of two basic modes, a packet mode and a circuit mode, was done. The packet mode was oriented toward statistical sharing of a channel, using a Carrier Sense Multiple Access (CSMA) scheme. This method can make very efficient use of a single 25 kHz channel, however it is not compatible with real-time applications. The circuit mode is oriented toward real-time application, being able to guarantee delivery time within the slot/frame structure provided.[26] It could be considered more inefficient in certain applications, however, since time slots not used remain idle. A total of seven future VHF system candidates were agreed upon and evaluated against future requirements and desirable features, and the circuit mode with Time Division Multiple Access (TDMA) architecture was selected as the best one.[27]

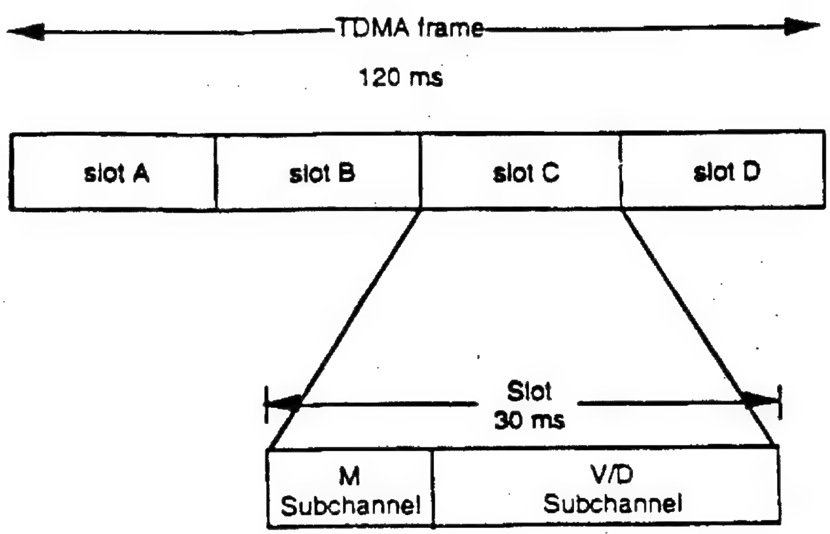

Figure 5.2 TDMA System Timing Hierarchy
Source: RTCA Special Committee-172, Document 225 "VHF Air-Ground Communications System Improvements Alternatives Study and Selection of Proposals for Future Action," RTCA, Inc., Washington, D.C., November 17, 1994, page 161.

[26] RTCA Special Committee-172, Document 224, page 22.

[27] RTCA Special Committee-172, Document 225, page 101.

The same 25 kHz channel spacing would be used as today in the VHF frequency range. However, using TDMA would allow for more capacity. The TDMA configuration would be based on a frame with a length of 120 ms. Each of these frames would be divided into four time slots of 30 ms each (see figure 5.2). Each of these time slots would be an independent circuit which could support two-way and real-time voice or data link applications in simplex fashion. These time slots would each contain a management subchannel and a voice/data subchannel. The management subchannel would contain necessary bit information for the operation of TDMA: ramp-up time, synchronization, system data, and propagation guard time. The voice/data subchannel components would be: ramp-up time, synchronization, a header field, user information, and propagation guard time.

Using TDMA allows for flexibility with its configuration. All four time slots could be used for voice-only operation, which would increase this capacity by four. Another alternative would be for one or more of the time slots to be reserved for data link applications, such as the implementation of ADS. The time slots could be assigned for voice or data as required. An advantage of using single channel TDMA is that voice and data are both supported on the same channel.

The operation of the voice communications would work in the same manner as today, in push-to-talk simplex mode. Digital modulation would code the voice resulting in a continuous periodic-burst bit stream in the voice time slots. Data

messages would be transmitted within the designated data time slots, with channel access reservations sent from the aircraft via slotted-aloha random access.[28]

One big disadvantage of using TDMA is that all the aircraft that are using the 25 kHz channel must be communicating with the ground station in order to keep synchronized. To establish this synchronization, the ground radio would have to send an 'initialization message' to the aircraft which would be contained in the uplink management subchannel. I also need to mention that ARINC's vast network of VHF ground radio stations would not have the capability to be used with this new system. Although the airlines will most likely continue to use ACARS and the ARINC network for many of their internal functions, the FAA has stated that it intends to limit its use to pre-departure clearances and ATIS (automatic terminal information service). New VHF ground stations having sufficient redundancy and integrity to implement the TDMA architecture have been estimated to have a cost of about $50,000 each.[29] These would be operated by the FAA.

Testing in Melbourne, Florida

Tests have been done in Florida, by Harris Corporation Air Traffic Control Systems Division, which use a VHF data link for the implementation of ADS. They have developed an all-weather (radar performance diminishes in bad weather) ADS system which has the capability to track an entire fleet of aircraft, in the air or

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[28] RTCA Special Committee-172, Document 225, page 68.

[29] Conversation with Jack Martin of Harris Corporation Air Traffic Control Systems Division, Melbourne, Florida.

on the ground, to within feet.[30] Harris has been testing this technology with aircraft from Florida Institute of Technology and Embry-Riddle University. In 1993, they put GPS receivers and VHF two-way digital data links in 25 of these aircraft and tested their ADS capability. In May of 1994, more trials were done using five aircraft flying from Melbourne International Airport to Harris control center with their location being depicted on a screen.

Testing is continuing at the present time using 36 aircraft to refine this VHF data link and the ADS systems. TDMA architecture is being used.[31] The aircraft, which include Piper PA-28 Cherokees and Mooney 201Js among others, are all equipped with GPS antennas and receivers, single-board processors, and VHF data link modems, which allow ground observers to track the aircraft without involving the pilots.[32] The VHF data link radios they are using at the present time are 4800 bps and soon they will be using 9600 bps radios. The cost per aircraft for this VHF data link at 4800 bps is costing them $1500, however the retail cost of a similar unit would be slightly more. They are using all commercial off-the-shelf components with their own software. The ground stations poll the aircraft through the VHF data link for their positions. Some are also carrying laptop computers so they can test digitized communications between the pilots and controllers. The VHF data link is

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[30] Klaus, Leigh Ann, "Avionics Advances Shape the Future of Flight," *Defense Electronics*, October, 1994, page 21.

[31] Conversation with Jack Martin of Harris Corporation Air Traffic Control Systems Division, Melbourne, Florida.

[32] McKenna, James T., "Harris Team Studies WAAS, Aircraft Tracking System," *Aviation Week and Space Technology*, April 3, 1995, page 66.

also being used to transmit DGPS corrections to the GPS receivers on board the aircraft. They are testing target acquisition schemes, tracking algorithms, and data link protocols, as well as the operational implications and how the resulting capabilities may fit into the evolving ATC system.[33] Richard Pitts of Harris Corporation said, "Tracking and acquisition of one plane is pretty simple but with 10 to 20 planes coming into the area, data link problems become more complex." Currently, Harris Corporation is able to support about 5 aircraft with a 1 second ADS update rate and about 25 aircraft with a 5 second ADS update rate by using this VHF data link. This brings up the question of maximum capacity.

VHF Capacity

Assume that we use VHF frequencies with 25 kHz channel spacing and the TDMA architecture which was determined to be the best option. The modulation scheme would be differentially encoded 8 phase shift keying (PSK), which would differentially encode the information with 3 bits per symbol transmitted as changes in phase. The symbol rate would be 10,500 symbols per second which allows a maximum bit rate of 31.5 kbps.[34] "This bit rate has not yet been achieved, but it will only be two or three years until we can," says Jack Martin of Harris Corporation.

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[33] McKenna, page 67.

[34] RTCA Special Committee-172, Document 224, page 31.

A study was done by RTCA of the VHF data link implementing TDMA at this data rate. The results showed that a notable TDMA data link capacity was possible, and that even during severe data loading at peak traffic periods, time-critical messages could be delivered without significant delays.[35] A simulation model showed that with forty aircraft, the total data slot utilization is 21% for the steady-state traffic and 78% for the peak traffic with an average message delay less than 1.5 seconds. With sixty aircraft, the total data slot utilization is 31% for the steady-state traffic and 116% for the peak traffic with an average message delay less than 2 seconds.[36] The maximum number of aircraft that can be handled by using TDMA can be estimated by observing that the TDMA system runs out of channel capacity at high traffic density with over 60 aircraft and at medium traffic density with over 80 aircraft.

MODE-S DATA LINK

Using VHF digital radios seems to be a viable option in regions where ADS messages can be transmitted via a line-of-sight digital data communications link. However, many proposals for establishing this air-ground data link involve using Mode-S transponders, which I will show has significantly more capacity than the VHF data link. Mode-S transponders transmit on the 1090 MHz frequency band for downlink and receive on the 1030 MHz frequency band for uplink. These are

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[35] RTCA Special Committee-172, Document 225, page 102.

[36] RTCA Special Committee-172, Document 225, page 254.

the same frequencies used by secondary surveillance radar systems and aircraft transponders today. Primary surveillance radar, sometimes referred to as "skinpaint," is when radar signals are reflected by an object (target aircraft) and then received back at the radar site. A radar surveillance beacon will typically have a "sweep" of about 4.8 seconds in a terminal area and about 12 seconds in en route areas. Measuring the time interval between transmission and reception of the radar signals and correlating the angular orientation of the antenna beam provides the means for getting measurements of range and azimuth;[37] then the aircraft position can be displayed on a radar screen for the controller.

Transponders in aircraft work in conjunction with the secondary surveillance radar beacon system. Although radar signals are capable of picking up aircraft (its skinpaint) even without a transponder, the radar beacons send out interrogations (secondary radar) which trigger the response of the transponders in aircraft. This response includes a 12-bit binary code for identification and pressure altitude information if available.

Mode-A transponders emit just the 12-bit binary code (4096 code combinations) which is set manually by the pilot in flight. When a controller verbally assigns a "squawk" to the pilot, he will set four digits (each between 0 and 7 for a total 4096 combinations) on the face of the transponder. This is the current method used for aircraft identification with radar surveillance. A Mode-C

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[37] Airman's Information Manual, Federal Aviation Administration, U.S. Department of Transportation, August, 1995, page 809.

transponder is connected to the aircraft's pressure altimeter for altitude encoding. If the aircraft has a Mode-C transponder, it is capable of transmitting this pressure altitude as well as its squawk code to the controller. However, because the interrogations are not addressed, the replies from aircraft which are close together may sometimes be garbled or overlaid.

Mode-S surveillance radar would partially solve this problem. Mode-S transponders provide address information, called the technical address, making it possible for them to be interrogated individually. As originally conceived, the Mode-S data link messages would be transmitted by an aircraft only when it was illuminated by the beam of a rotating ground radar antenna.[38] The Mode-S radar beacon would repeatedly send out a "roll call" of interrogations individually addressed to each aircraft in the area. These would be sent out in an order which would preclude replies from being overlaid or garbled. Every so often the Mode-S radar beacon would send an "all call" interrogation which would elicit replies from any aircraft that had just flown into the area. Now the Mode-S ground station would have the technical address of this aircraft and would thereafter interrogate it in the "roll call." Once it had an aircraft on the "roll call," the Mode-S ground station would transmit information to that aircraft telling it not to respond to any more "all calls." In this way there are not an excessive amount of replies to the "all call."

[38] Klass, Philip J., "Novel ATC Technique to Undergo Tests," *Aviation Week and Space Technology*, August 16, 1993, page 38.

Although it was conceived in this way as an improvement to the ATC radar beacon system, the actual implementation of Mode-S evolved and began as part of the Traffic-alert and Collision Avoidance Systems (TCAS) which are in use today. In aircraft with TCAS equipment, Mode-S transponders *broadcast* spontaneous periodic messages called squitters. Mode-S transponders currently transmit a 56-bit squitter once every second, which includes the 24-bit technical address of the aircraft. The actual time between squitter transmissions is random and varies by a couple tenths of a second so that interference with other squitters can be avoided.

Traffic-alert and Collision Avoidance Systems

The idea for a ground-independent airborne collision avoidance system originated after a mid-air collision of two airliners over the Grand Canyon in 1956.[39] In recent years, safety of flight has improved because of the development of TCAS equipment which warns pilots of possible traffic conflicts. TCAS equipment works very much like ATC radar. It acts as an active interrogator of the transponders in other aircraft, which respond to these interrogations in the same way they respond to interrogations from a surveillance radar beacon on the ground.

TCAS 1 gives a warning to the pilot that there is another aircraft in close proximity. This warning is called a traffic advisory. It can help the pilot visually locate other aircraft and give him added crucial seconds to maneuver accordingly.

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[39] Reardon, Peter, "Close Encounters," *Asia-Pacific AIR SAFETY*, November, 1994, page 9.

TCAS 1 works as long as the other aircraft has any of the various forms of transponder, and nearly all aircraft are so equipped.

Further developments led to TCAS 2, which offers resolution advisories as well as traffic advisories to the pilot. These resolution advisories give recommended escape maneuvers to pilots in the vertical plane. For example, recommending that the pilot descend to avoid the traffic. The TCAS 2 resolution advisories, which provide both displayed and audible information, require that the other aircraft be equipped with at least a Mode-C transponder, which is required in a significant amount of airspace and is standard equipment on almost every aircraft. If both aircraft are TCAS 2 equipped, then a Mode-S data interchange permits each aircraft to coordinate its resolution with the other.

In response to the 1986 collision between an AeroMexico airliner and a general aviation aircraft over Cerritos, California, which killed 82 people,[40] the U.S. Congress ordered that TCAS 2 equipment be put in all commercial aircraft with more than 30 seats. This mandate has been in effect since the end of 1993; an estimated 3500 to 4000 commercial aircraft have been retrofitted with TCAS 2.[41] The FAA is requiring that TCAS 1 be installed on all commercial aircraft with 10 to 30 seats by the end of this year. TCAS equipment appears to have had a positive impact because there has not been a mid-air collision of commercial aircraft since

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[40] Lopez, Ramon, "Too Close for Comfort," *Flight International*, January 18, 1995.

[41] Long, Michael, "Coaxial Switch Technology for Collision Avoidance Systems," *Microwave Journal*, December, 1991, page 96.

the mandate.[42] The reason that TCAS equipment is not required in all aircraft is because the current cost is estimated at over $100,000 per aircraft. The TCAS unit itself costs about $80,000, the pilot display $16,000, the control unit $8,000, and the wiring kit another $8,000.[43] The Mode-S transponders which are used by the airlines which can interface with these TCAS units costs about $24,000 each. A non-diversity Mode-S transponder which cannot interface with a TCAS unit is in the range of $8,000 to $15,000. Keep in mind, however, that these are more elaborate Mode-S transponders than would be necessary for a general aviation aircraft. Currently, there is only one avionics manufacturer, Bendix/King, who offers a panel mount Mode-S transponder for general aviation, the KT-70; it costs about $2,700.[44] The expense of mandated TCAS equipment does not seem to be opposed by the commercial airlines, however, probably due to the added level of safety it provides and the fact that it is not good for their public relations to oppose anything which improves safety.

There is always room for improvement, however, and work is being done to develop TCAS 4 which will incorporate GPS position information so that horizontal resolution advisories can be provided as well as vertical resolution advisories. TCAS 3 was an attempt to do this without GPS and was abolished.

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[42] Klaus, page 25.

[43] Conversation with Paul Nef of Honeywell Air Transport Systems Division, Phoenix, Arizona.

[44] Bayliss, E.T., et al., "Demonstration of GPS Automatic Dependent Surveillance of Aircraft Using Spontaneous Mode-S Broadcast Messages," *NAVIGATION: Journal of The Institute of Navigation*, Summer, 1994, page 191.

Horizontal resolutions would require that both aircraft be equipped with a Mode-S transponder which could transmit aircraft GPS position information and a velocity vector. The TCAS 4 equipment will listen for squitters sent out by other aircrafts' Mode-S transponders. Because these squitters contain the address of the sender, TCAS 4 can individually interrogate each aircraft in its vicinity. It will receive replies containing their GPS location, providing the means for better resolution advisories.

Both FAA officials and the TCAS manufacturers, which include AlliedSignal, Rockwell Collins, and Honeywell, believe that having TCAS equipment with Mode-S on commercial passenger aircraft will eventually become an international standard.[45] In the next section I will analyze the results of tests done which use Mode-S to implement the ADS concept.

Tests at Hanscom Field

The squitters transmitted by Mode-S transponders, for use by current TCAS equipment, are made up of a 56-bit message field. These squitters contain the 24-bit technical address of the aircraft, 8 control bits, and 24 parity bits. In order for Mode-S transponders to be used for ADS, it is necessary to use an *extended squitter*. This extended squitter contains a 56-bit ADS message (see figure 5.3) containing the information discussed in the previous chapter, which includes the aircraft's GPS location. So the Mode-S extended squitters used for ADS will

[45] Lopez, Ramon, "Too Close for Comfort," *Flight International*, January 18, 1995.

consist of a 112-bit message field. The extended squitter is also what will make the development of TCAS 4 possible.

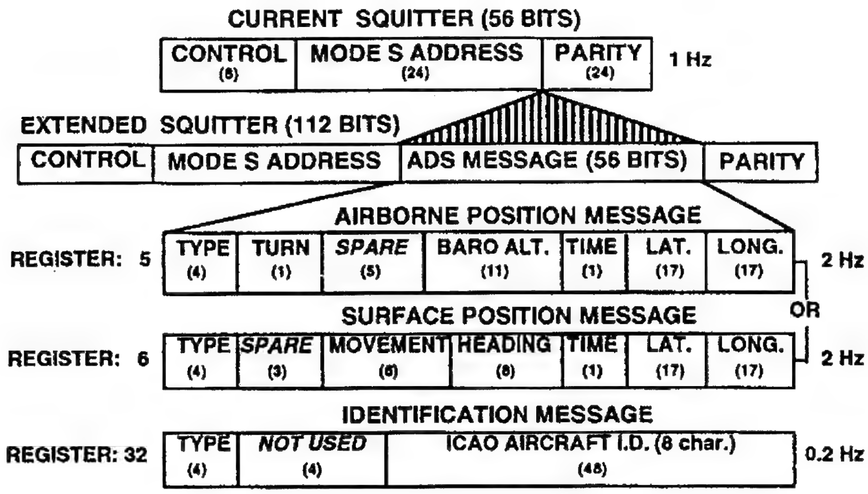

Figure 5.3 Mode-S Extended Squitter Format

Source: Bayliss, E.T., et al., "Demonstration of GPS Automatic Dependent Surveillance of Aircraft Using Spontaneous Mode-S Broadcast Messages," *NAVIGATION: Journal of The Institute of Navigation*, Summer, 1994, page 191.

The feasibility of using Mode-S extended squitters for the implementation of ADS has been tested in Bedford, Massachusetts at Hanscom Field. This project was sponsored by the FAA but was performed by the Massachusetts Institute of Technology Lincoln Laboratories. The objective of the field tests was to show that the Mode-S extended squitter could be used to downlink ADS position information. The tests also demonstrated that the Mode-S data link could be used to transmit DGPS corrections to aircraft.

The ground equipment used for the tests were reported as a DGPS reference station, a ground station, a central computer, and a display system. The ground station was a modified TCAS unit capable of receiving the extended squitters and

transmitting data link messages. An omnidirectional DME antenna was connected to the ground station which they anticipated would give them a range of 50 nautical miles (nmi). The aircraft used was a Cessna 172 equipped with a GPS receiver, an airborne computer processor, and a modified Mode-S transponder capable of transmitting the extended squitter and receiving data link messages.

In the tests, the current 56-bit Mode-S squitter was broadcast once every second just as before so that they could maintain compatibility with TCAS equipment. In addition, extended squitters of 112-bits were broadcast. The 56-bit ADS message field which was contained in these extended squitters had three different forms:[46] an air surveillance format and a surface surveillance format, both of which provided position information, and a flight identification format, which is the flight number for commercial aircraft or the tail number for general aviation aircraft (see figure 5.3). The extended squitters in the air surveillance format (or surface surveillance format if not airborne) were broadcast twice each second to increase the chance of successful reception and the flight identification format was broadcast once every five seconds.

The Cessna 172 was flown out to a range of 110 nmi at 10,000 feet altitude and then back at 9,000 feet altitude. The Mode-S transponder in the aircraft broadcast extended squitters in the air surveillance format containing its GPS position. The results can be seen in figure 5.4. Small black dots are used to

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[46] Orlando, Vincent A., et al., "GPS-Squitter: System Concept, Performance, and Development Program," *The Lincoln Laboratory Journal*, volume 7, number 2, 1994, page 147.

indicate that an extended squitter was received by the ground station within 3 seconds of the previous one, an open circle to indicate between 3 and 5 seconds, and a square to indicate that it was more than 5 seconds before an update was received.[47]

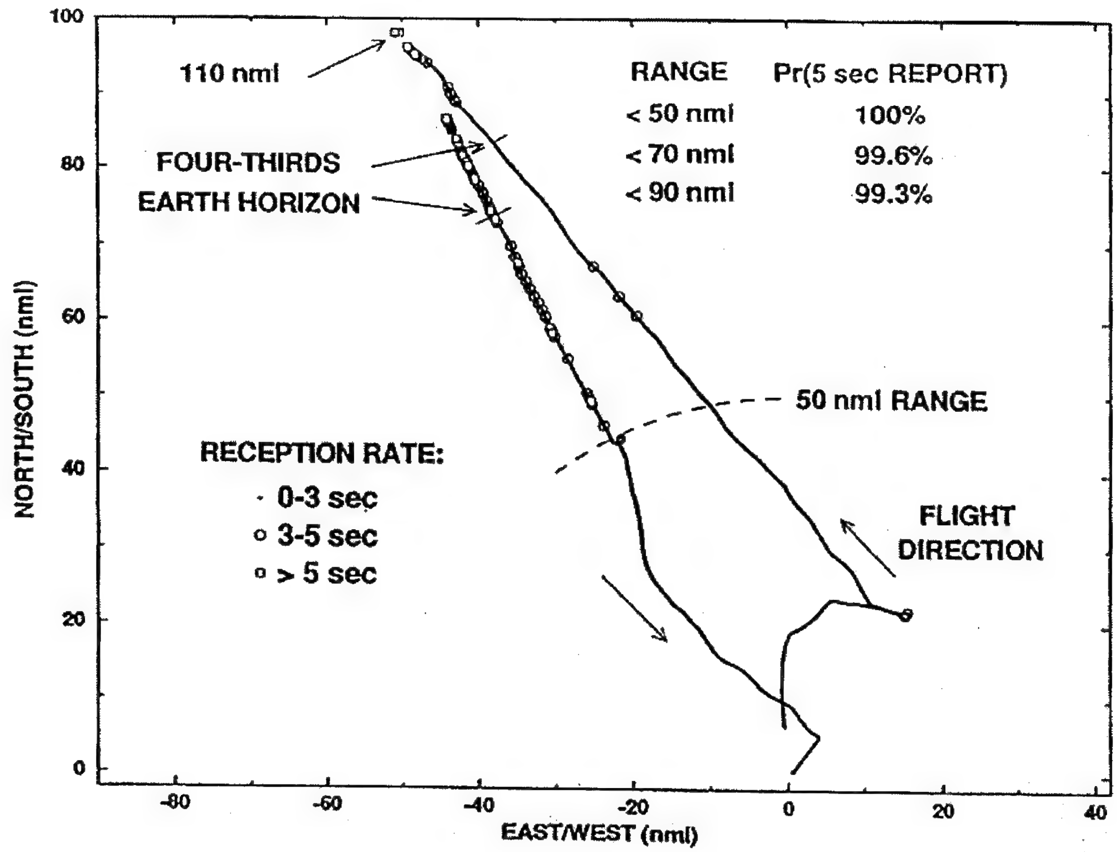

Figure 5.4 Hanscom Field Test Results

Source: Boisvert, Robert E., et al., "GPS-Squitter Experimental Results," Proceedings of the 13th Digital Avionics Systems Conference, Phoenix, Arizona, October 31 - November 3, 1994, page 5.

The results were further analyzed by comparing the update rate to that of a standard radar surveillance beacon, which is about 5 seconds in a terminal area and 12 seconds en route. It can be seen in figure 5.4 that within 50 nmi of the ground

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[47] Boisvert, Robert E., et al., "GPS-Squitter Experimental Results," Proceedings of the 13th Digital Avionics Systems Conference, Phoenix, Arizona, October 31 - November 3, 1994, page 4.

station at Hanscom Field at least one extended squitter was received in every 5 second period. Outside of 50 nmi, the results were nearly as good. I feel that these results show that the Mode-S extended squitter can be very reliable. These experiments were done with an omnidirectional DME antenna with a maximum gain of 9 dB. For en route purposes which desire a greater range, a six sector antenna is anticipated to be used which would increase the maximum gain to about 16 dB and increase the range from 50 to 100 nmi. An even greater range could be achieved if a higher gain antenna were used, which would require more separate sectors. On the surface of the field, with the aircraft broadcasting extended squitters in the surface surveillance format and with two ground stations on the field, a once per second update was achieved 99.6% of the time.[48]

Trials have also been done at Logan International Airport in Boston, Massachusetts to test the implementation of ADS by using the Mode-S extended squitter. These tests used a Cessna 421 and a Cessna 172. The technology was shown to perform very well for both surface and air surveillance.[49] Bendix/King is working to add the extended squitter capability to its panel mount Mode-S transponder which is available for general aviation, as well as an uplink capability for DGPS, traffic information, and graphical weather messages.[50] This will add slightly to the cost of the unit, which is currently $2,600.

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[48] Boisvert, page 4.

[49] Knittel, George H., "Extended Mode-S Squitter Program Status and Plans," Lincoln Laboratory, Massachusetts Institute of Technology, September 30, 1994, page 1.

[50] Bayliss, page 191.

Mode-S Capacity

As I mentioned earlier, Mode-S transponders transmit at the 1090 MHz frequency band. The use of Mode-S extended squitters implies that there is no formal protocol such as was the case with TDMA for the VHF channels. The reporting protocol for the Mode-S channel is random, and it has to be random because of the other random traffic already using the 1090 MHz frequency band (secondary surveillance radar and TCAS systems). However, the 1090 MHz downlink frequency allows for a high bit rate of 1 Mbps.[51]

Because these extended squitters are random, the limiting factor as far as capacity will be the interference from other traffic on the channel. The extended squitters are 112 bits, which translates to a length of 120 μsec at the 1090 MHz frequency band. The 56 bit TCAS squitters have a length of 64 μsec and the secondary surveillance radar replies have a length of 20 μsec. Whenever two of these data messages arrive at a receiver at about the same time, they have a collision and both are destroyed. Therefore, there will be a maximum number of aircraft and reply rates which will keep the amount of these collisions at an acceptable level.

Dr. Orlando at Lincoln Laboratories did a study using analytical methods to determine this limit based on the limitations of interference. The minimum

[51] Klass, Philip J., "Navsats Promise New ATC Horizons," *Aviation Week and Space Technology*, January 18, 1993, page 29.

acceptable ADS criteria he chose was a 99.5% probability of receiving at least one ADS squitter update from an aircraft every five seconds. He used the Poisson model to calculate the probability of successful squitter replies. Dr. Orlando's results estimated that the maximum number of aircraft that could be supported by an omnidirectional antenna would be 85 and the maximum number supported by a six sector antenna would be 215. These results were conservative in that worst case values were used for the number of radar interrogations and other Mode-S squitters that could cause interference.[52] Later, Dr. Ringel at Unisys Government Systems Group developed a simulation model which made more accurate assumptions of the Mode-S system behavior, which he determined could not be treated as a Poisson process. A comparison of Dr.Ringel's simulation results and Dr. Orlando's results

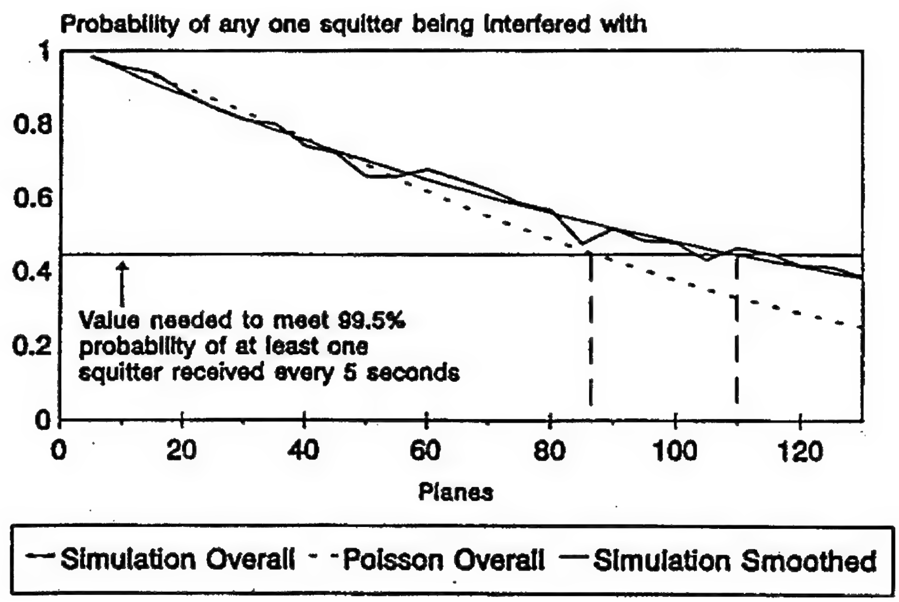

Figure 5.5 Mode-S Squitter Interference Probability

Source: Ringel, Emanuel, "Improved Estimate of ADS-Mode S Capacity," Proceedings of the 39th Annual Air Traffic Control Association Convention, Arlington, Virginia, September 18-22, 1994, page 138.

[52] Orlando, Vincent A., and Harman, William H., "GPS-Squitter Capacity Analysis," Lincoln Laboratory, Massachusetts Institute of Technology, May 20, 1994, page 4.

with its Poisson assumptions is in figure 5.5. Dr. Ringel's results estimated that the maximum number of aircraft that could be supported by an omnidirectional antenna would be 110 and the maximum number supported by a six sector antenna would be 275. Also worth noting is that if some of the other random traffic on the channel is eventually removed, such as the interrogations from secondary surveillance radar which would not be necessary with full ADS implementation, then the capacity would go up dramatically (to as much as 700 or 1400 aircraft with a sector antenna)[53]. Even with this traffic, however, I believe that the Mode-S extended squitter system has more than sufficient capacity to support the implementation of ADS.

CAPACITY COMPARISON

We have seen the results of studies done to determine the capacity of both a VHF digital data link using TDMA and a Mode-S digital data link using extended squitters. Both methods seem to have the necessary capacity to effectively implement ADS under most conditions. It appears that under extremely heavy traffic loads, however, that the Mode-S option would fare better. With expected significant growth in the number of flights in the future, I wonder if the VHF digital data link would be enough.

[53] Bayliss, E.T., et al., "Aircraft Surveillance Based on GPS Position Broadcasts from Mode-S Beacon Transponders," Proceedings of the Institute of Navigation GPS-94, Salt Lake City, Utah, September 22-24, 1994, page 11.

A direct comparison was done at Stanford University between the capacity of these two data communications links. First they showed that the capacity of a channel with an organized protocol such as TDMA is higher than the capacity of a random protocol channel, as long as the message length is longer than the propagation delay guard band.[54] This, however, does not take into consideration the bit rates. For the comparison, they calculated the maximum capacity for an organized protocol at 30 kbps (VHF) and for a random protocol at 1 Mbps (Mode-S), the two options for the implementation of the ADS concept. They required an update rate of 5 seconds, the same as achieved today at terminals with surveillance radar. The Mode-S capacity was computed assuming 8 squitters were transmitted in the 5 second period and the VHF capacity was computed using the number of time slots available in the 5 second period. The results can be seen in figure 5.6, along with the capacity calculated for an organized channel at 1 Mbps, which would not be possible unless the other traffic on the 1090 MHz channel were phased out. As expected, the Mode-S data link shows a higher capacity and therefore seems to be the better option.

[54] Gazit, Ran, and Powell, David J., "Communication Protocols for GPS-based Surveillance and TCAS," Department of Aeronautics and Astronautics, Stanford University, 1993, page 9.

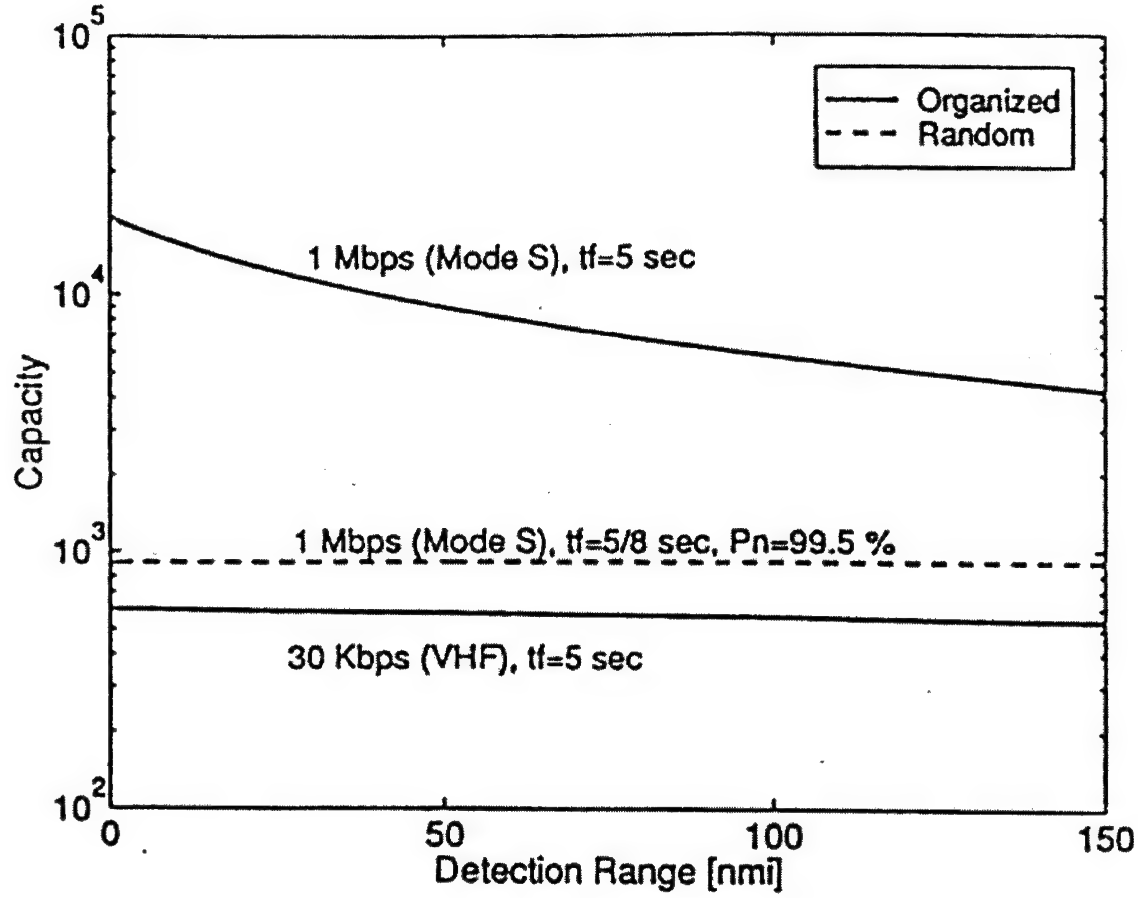

Figure 5.6 Mode-S / VHF Capacity Comparison

Source: Gazit, Ran, and Powell, David J., "Communication Protocols for GPS-based Surveillance and TCAS," Department of Aeronautics and Astronautics, Stanford University, 1993, page 9.

CHAPTER 6

CONCLUSIONS / RECOMMENDATIONS

In this thesis, I have discussed the nature of the ATC system under a satellite-based navigation environment. I described the current methods of exercising air traffic control and airborne navigation. I determined that, with the number of flights today and the demand for even more flights in the future, the air traffic system as it exists has reached its capacity for providing assured safety. I described the problem areas as being congested radios, airspace without sufficient surveillance, indirect and inefficient routing, excessive separation standards, and lack of all-weather landing capability at most airports. I proceeded to show how the use of the Global Positioning System for navigation and landing and the Automatic Dependent Surveillance system concept for data transfer and worldwide surveillance could solve these problems.

A description of the concepts of the Global Positioning System was given, including the methods it uses to achieve such incredible accuracy and the measures taken to assure its integrity. The benefits of augmentation of the GPS signals by implementing Differential GPS were shown to be critical for the application of precision approaches.

I then described the Automatic Dependent Surveillance system concept, without which the full benefits of GPS navigation cannot be realized. I showed

how ADS could improve the safety of flight operations, accommodate user-preferred flight profiles, and increase airport and airspace capacity to meet the demands of future air traffic.

I then investigated the techniques proposed for establishing the digital data communications link which ADS requires. I described the extent to which these techniques have been evaluated and compared them in terms of their capacity, their demonstrated test results, and their cost of implementation.

I determined that over oceans and remote regions where line-of-sight digital communications are not possible, satellite communications are necessary to implement ADS. The growth of traffic in these regions will require ADS for efficient use of the airspace. The satellite systems and avionics for satellite communications are well under development and I anticipate that the operational trials which are continuing at the present time will lead to full ADS capability within a year or two. If it were not for the high cost of satellite communications, the problem of choosing a data communications link for implementing ADS would be solved for all aviation users on a worldwide basis.

Over continental regions, which are more congested and contain aircraft of a wide range of sophistication, ADS messages will be transmitted via a line-of-sight digital communications link. I identified the two options as Mode-S and VHF. I believe that it is important to choose only one standard so that uniformity is maintained for the purpose of airborne collision avoidance systems which can be developed for all aircraft. I believe that the modified Mode-S transponder,

broadcasting extended squitters, is the optimal solution to the problem of determining the digital data communications standard which will be used for implementing ADS.

One advantage Mode-S has is that it is already fully ICAO standardized because of its current operational use in TCAS systems on the radar beacon frequencies. Therefore, there should not be any problems with spectrum allocation. The use of VHF as a digital data link does not presently have international standards, although they are being developed.

I considered the capacity of the data link as a very important discriminating factor. Although the tests and analytical simulations of the capacity of the Mode-S extended squitter and the VHF data link using TDMA showed that both seem to be a viable option, Mode-S was shown to have significantly more capacity than VHF. Thinking in terms of future growth of airborne traffic, this strongly supports my recommendation that Mode-S be used to implement the ADS system concept.

However, the digital data communications link chosen must be inexpensive enough to meet the needs of the full spectrum of aviation users. Looking at the cost of each system, including the airborne avionics and the ground stations required, both options seem to be reasonably comparable on economic terms. The VHF avionics are estimated to be in the $1,500 to $3,000 range for general aviation use and the supporting ground stations about $50,000 each. The Mode-S avionics for general aviation are estimated to be on the high side of $2,600 per transponder. The supporting Mode-S ground stations, which are modified versions of existing

TCAS equipment and DME antennas, are about $100,000 each. This is only about one tenth what it would have cost for a Mode-S radar beacon system. I concede that Mode-S is still more expensive than VHF, but not as dramatically as most people think. I believe that it is affordable for all aviation users if its use is phased in over a period of years.

This transition period from the current ground-based air navigation system with radar surveillance to the future satellite-based system using ADS is another issue. The advantage that is inherent in the use of Mode-S transponders is that, as a single unit, it provides compatibility for ADS and radar beacon interrogations. This interoperability allows operation in regions using either surveillance technique. Therefore, a smooth transition is possible.

Hence, I propose that the use of Mode-S be universally adopted as the digital data communications standard for the implementation of Automatic Dependent Surveillance.

GLOSSARY OF ABBREVIATIONS

ACARS	Aircraft Communications Addressing and Reporting System
ACK	Acknowledgment Signal
ADS	Automatic Dependent Surveillance
AMSS	Aeronautical Mobile Satellite Services
ARINC	Aeronautical Radio, Incorporated
ARTS	Automated Radar Tracking System
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATN	Aeronautical Telecommunications Network
CAA	Civil Aviation Authority
C/A-code	Coarse Acquisition Code
CDMA	Code Division Multiple Access
CNS/ATM	Communication, Navigation, Surveillance and Air Traffic Management
CSMA	Carrier Sense Multiple Access
DGPS	Differential Global Positioning System
DOD	Department of Defense
DOT	Department of Transportation
DSB-AM	Double-Sideband Amplitude Modulation
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FDMA	Frequency Division Multiple Access
GDOP	Geometrical Dilution of Precision
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HF	High Frequency
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
Inmarsat	International Maritime Satellite Organization
ITU	International Telecommunications Union
LADGPS	Local Area Differential GPS
MTSAT	Multifunctional Transport Satellite (Japan)
NAK	Negative Acknowledgment Signal
NAS	National Airspace System
NASA	National Air and Space Association
Navstar	Navigation Satellite Time and Ranging
NDB	Non-Directional Beacon
nmi	Nautical Mile (1.15 statute mile)

NNSS	Navy Navigational Satellite System
OSI	Open Systems Interconnection
P-code	Precise Code
PPS	Precise Positioning Service
PRN code	Pseudo-Random Noise Code
PSK	Phase Shift Keying
RTCA	Radio Technical Commission for Aeronautics
SA/AS	Selective Availability / Anti-Spoof
SARPs	Standards and Recommended Practices
Satcom	Satellite Communications
SCPC	Single Channel Per Carrier
SPS	Standard Positioning Service
TACAN	Tactical Air Navigation
TCAS	Traffic-Alert and Collision Avoidance Systems
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
Tracon	Terminal Radar Approach Control
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR/DME	VHF Omnidirectional Range/Distance Measuring Equip
VORTAC	Collocated VOR & TACAN
WAAS	Wide Area Augmentation System
WADGPS	Wide Area Differential GPS
Y-code	Encrypted P-code

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PHONE INTERVIEWS

Ed Anderson of AlliedSignal Aerospace, Redmond, Washington.

Bob Bernard of the Federal Aviation Administration, Navigation Office, Washington, D.C.

Ken Bodensteiner of Rockwell International Collins Air Transport Division, Cedar Rapids, Iowa.

Harold Brackett of Harris Corporation Air Traffic Control Systems Division, Melbourne, Florida.

Pete Conner of C3Sat International, San Antonio, Texas.

Rod Gunther of Honeywell Air Transport Systems Division, Phoenix, Arizona.

Ken Lauterstein of the Federal Aviation Administration, GPS Office, Washington, D.C.

Jack Martin of Harris Corporation Air Traffic Control Systems Division, Melbourne, Florida.

Hal Moses of Radio Technical Commission for Aeronautics, Washington, D.C.

Paul Nef of Honeywell Air Transport Systems Division, Phoenix, Arizona.

Bill Thompson of the Department of Transportation, Transportation Systems Center, Boston, Massachusetts.

Paul Wolfgram of Magnavox Electronic Systems Company, Fort Wayne, Indiana.